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GÖTEBORGS KUNGL. VETENSKAPS- OCH VITTERHETS-SAMHÄLLE

REPORTS OF THE SWEDISH DEEP-SEA EXPEDITION 1947—1948

EDITED BY

HANS PETTERSSON

SCIENTIFIC LEADER OF THE EXPEDITION

VOLUME V

Sediment Cores from the East Pacific

FASC. 1

BY

GUSTAF ARRHENIUS

GÖTEBORG
ELANDERS BOKTRYCKERI AKTIEBOLAG

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SEDIMENT CORES FROM THE EAST PACIFIC

PART 1

PROPERTIES OF THE SEDIMENT AND THEIR DISTRIBUTION

BY

GUSTAF ARRHENIUS

Contents

Page

Introduction 6
Acknowledgements 7
Chapter 1.0 Systematics 8
§ 1.0.1 Disposition of the work. Reference system 8
.2 Units, constants, and symbols 8
.3 Diagrams 9
.4 Classification of pelagic deposits 11

Chapter 1.1 Calcium carbonate 12
§ 1.1.1 Origin and nature of carbonates 12
.2 Factors determining the concentration of calcium carbonate 12
.3 Present distribution 13
.4 Interpretation of the present eupelagic distribution 15
.5 Stratigraphical distribution 16
.6 Interpretation of the eupelagic stratigraphical distribution 18

Chapter 1.2 Titanium, absolute chronology, and rate of accumulation 23
§ 1.2.1 Previous work 23
.2 Aims and conditions of the present investigation 24
.3 Theoretical considerations 25
.4 Checking of deviations in the lutite accumulation 25
.5 Results 27
.6 Time-density relationships of the lutite veil 28
.7 Obstacles for regional extrapolation 29
.8 The titanium content as an indicator of absolute age 29
.9 Calculation of rate of accumulation 30
.10 Titanium content of the eupelagic lutite 30

Chapter 1.3 Biogenous silica 31

Chapter 1.4 Organic matter (marine humus) 32
§ 1.4.1 Previous work. Apparent disagreements and agreements 32
.2 Regional distribution 33
.3 The carbon-nitrogen relationship 36
.4 Posthume diagenetical changes of the organic matter 39

Chapter 1.5 Phosphorus 41
§ 1.5.1 Previous work 41
.2 Distribution of phosphorus in pelagic clays 41
.3 Distribution in the calcareous East Pacific Ridge sediments. Association with manganese 45
.4 Distribution in the East Eupelagic carbonate area 47

Chapter 1.6 Colour and pattern 49
§ 1.6.1 Scope and limitation of the investigation 49
.2 Significance of colour 50
.3 Pattern of East Pacific deposits 50

Page

Chapter 1.7 Foraminifera 51
§ 1.7.1 Aims and scope of the investigation 51
.2 Concentration of foraminifera 51
.3 Variations in composition of the planktonic fauna 55
.1 *Globorotalia* and *Globigerina* 55
.2 *Orbulina universa* 58
.3 *Pulleniatina obliquiloculata* 60
.4 *Sphaeroidinella dehiscens* and *Sphaeroidina bulloides* 61
.4 Concentration of benthonic foraminifera 62

Chapter 1.8 Radiolaria 65
§ 1.8.1 Scope and limitation of the study 65
.2 Concentration of radiolaria in the East Pacific sediments 65
.3 Distribution in the North Equatorial clay area 66
.4 Distribution in the East Eupelagic carbonate area 66

Chapter 1.9 Size distribution of *Coscinodiscus nodulifer* 67
§ 1.9.1 Observations leading to the study 67
.2 Results 67
.3 Previous knowledge of the factors determining the size of centric diatoms 71
.4 Interpretation of the results 72

Chapter 1.10 Other fossils 73
§ 1.10.1 Scope and limitation of the study 73
.2 Sponge remains 74
.3 Fish teeth and annelide jaws 75
.4 »Mollusc fragments» 76

Chapter 1.11 Rock fragments and mineral grains 77
§ 1.11.1 Scope and limitation of the study 77
.2 Glass, palagonite and »other mineral grains» 77
.3 Manganese micronodules 78

Chapter 1.12 Salinity, water, and density relations, and diagenesis of the sediment 78
§ 1.12.1 Salinity and water content 78
.2 Calcium carbonate-salinity relationship 81
.3 Volume-weight relationships 83
.4 Strength 84
.5 Reworking 86
.6 Recrystallization and chemical redistribution after deposition 87
.7 Water content-pressure relations 89

Introduction

The present volume constitutes a report on the sediment cores collected by the Expedition in the East Equatorial Pacific Ocean. It is intended to be a contribution to the knowledge of the Late Cenozoic geological evolution of the area and of pelagic stratigraphy and sedimentation in general.

The route in the East Pacific (fig. 1.0, at the end of this part) was determined by the combined hydrographical and geological interest of crossing the Equatorial Current System, which according to previous knowledge appeared to determine the facies conditions in this area. The core stations were selected so that as many cores as possible should be raised in a not too rough topography as the supply of coring tubes was restricted (cf. KULLENBERG, vol. IV). Failing of the corer caused the loss of core 49 and this, followed by a day of repair, resulted in a comparatively great distance between the long cores 48 and 51. In this area only a short open tube corer could be used (core 50 A). A Sunday caused the gap between cores 58 and 59.

Before the location of the station was

selected, the bottom topography was investigated by means of the echograph. When a suitable place was found, the ship usually continued on its course for appr. five minutes and then turned back. Owing to difficulties in returning to exactly the chosen point, these precautions did not always ensure favourable topographical conditions in the East Pacific Ridge Area where abrupt irregularities in the landscape frequently occur. In each case an attempt was made to collect also a short sediment core containing the undisturbed surface layer of the deposit. On account of failing of the corer and other circumstances this was unsuccessful in a number of cases. The stratigraphical study of the long and short cores indicates that when using a 10 m long piston corer in calcareous deposits, the top appr. 20 cm of the column are lost because of smearing along the walls of the lining tubes (cf. KULLENBERG, vol. IV of this report). The use of a 15 m long piston corer appears to cause the loss of appr. 40 cm of the top when highly calcareous sediments are sampled. In pelagic clays the truncation appears to be much less extensive and is believed usually to comprise only a few centimeters.

When planning the analytical treatment of the sedimentary material (cf. ARRHENIUS 1949) it was decided that this treatment should be divided in two main phases, the first one comprising routine analyses in all samples, without exception, of properties believed to be of general petrographical and stratigraphical interest. This group of analyses comprised the total number of samples gained from the material of the expedition, viz. appr. 16 000 samples. The second phase of the analytical work comprised special investigations required for the solution of stratigraphical and petrological problems arising during the work. Both the analysis and the collocation and interpretation of the results were carried out at the Kagghamra Laboratory, Grödinge.

The results gained are based upon appr. 50 000 analytical values. It should be stressed that the present treatment is far from exhaustive and deals with only a few of the important problems, the study of which has been made possible by Dr. Börje Kullenberg's invention, construction and application of the piston corer, and by Professor Hans Pettersson's leadership directing the Swedish Deep Sea Expedition 1947—1948.

Acknowledgements

The author is greatly indebted to Professor Hans Pettersson, Leader of the Swedish Deep Sea Expedition, for the privilege of working as the geologist of the Expedition, for having been permitted to choose the collection from the East Pacific for a closer study and for his generous support of the work.

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To Dr. Fritz Koczy and Dr. Nils Jerlov, the writer is grateful for valuable advice and for stimulating discussion of the statistical and oceanographical problems involved in the study.

The author's thanks are also due to Professor Carl Correns, Professor Philip Kuenen, Dr. Stina Gripenberg, Professor Fred B. Phleger, Dr. Cameron D. Ovey, Professor Carl G. Rossby, Dr. Alf Nyberg, Professor George de Hevesy, Dr. Heinz Lowenstam, and

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Finally the author wishes to express his gratitude to the printers, Elanders Boktryckeri A. B. for helpfulness and consideration during the printing of this volume and to all those, not mentioned above, who have contributed to the preparation and the carrying out of the investigation.

1.0 Systematics

1.0.1 Disposition of the work. Reference system.

The present report on the sediment cores from the East Pacific Ocean has been divided into five separate parts which together make up vol. V of the Reports of the Swedish Deep Sea Expedition 1947—1948. Part 1 contains the report on the general distribution of properties in the sediments together with the interpretation of the distributions and relationships found. Part 2 consists of a description of the sediment cores with suggested detailed interpretations. Part 3 forms a summary of the Late Cenozoic stratigraphy and geological evolution of the East Pacific pelagic area and part 4 accounts for the methods used in the study of the sediment cores. Part 5 is planned to contain special contributions to associated problems.

All plates have been collected separately in an appendix to part 2 in order to facilitate reading.

For references within the volume there has been employed a class reference system of the type widely used in modern scientific and technical literature referring to the contents of the paragraph cited instead of the page number. The parts of the volume are thus designated 1, 2, 3, 4, and 5, the chapters e. g. of part 1 are 1.0, 1.1, 1.2, etc. and the paragraphs e. g. of chapter 1.4 are designated 1.4.1, 1.4.2, 1.4.3, etc. A reference to § 2.60.12 thus refers to § 12 (which in part 2 always deals with the diagenesis of the sediment) in chapter 60 (which corresponds to core 60) in the descriptive part 2. A classed pagination corresponding to the contents of the text in the beginning of each page, has been printed in bold-face type in the right upper corner of the left page and in the left upper corner of the right page. The illustrations and tables are labelled according to the same principles, and fig. 1.4.3.2 thus refers to the second figure of § 3 in chapter 4 (Organic matter) of part 1.

A complete review of previous investigations of pelagic sediments from the Pacific Ocean has been given by Revelle (1944, p. 2—5).

1.0.2 Units, constants and symbols.

The unit of rate of accumulation (rac), rate of deposition, and rate of production has been

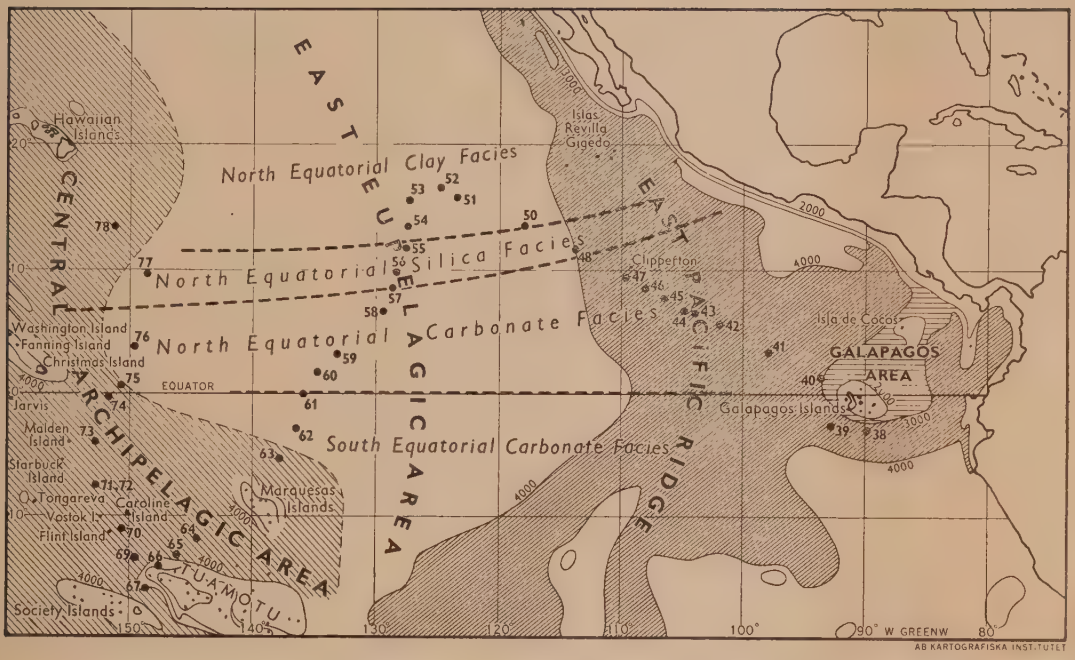

Fig. 1.0. Location of cores and environmental subdivision of the East Equatorial Pacific.

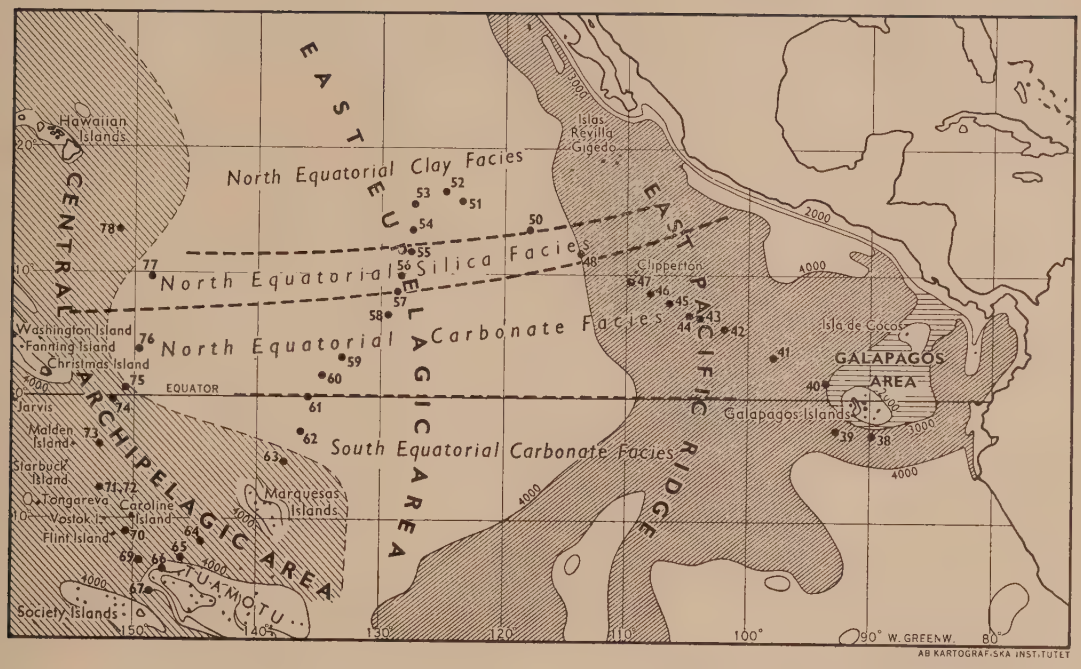

Fig. 2.0. Location of cores and environmental subdivision of the East Equatorial Pacific.

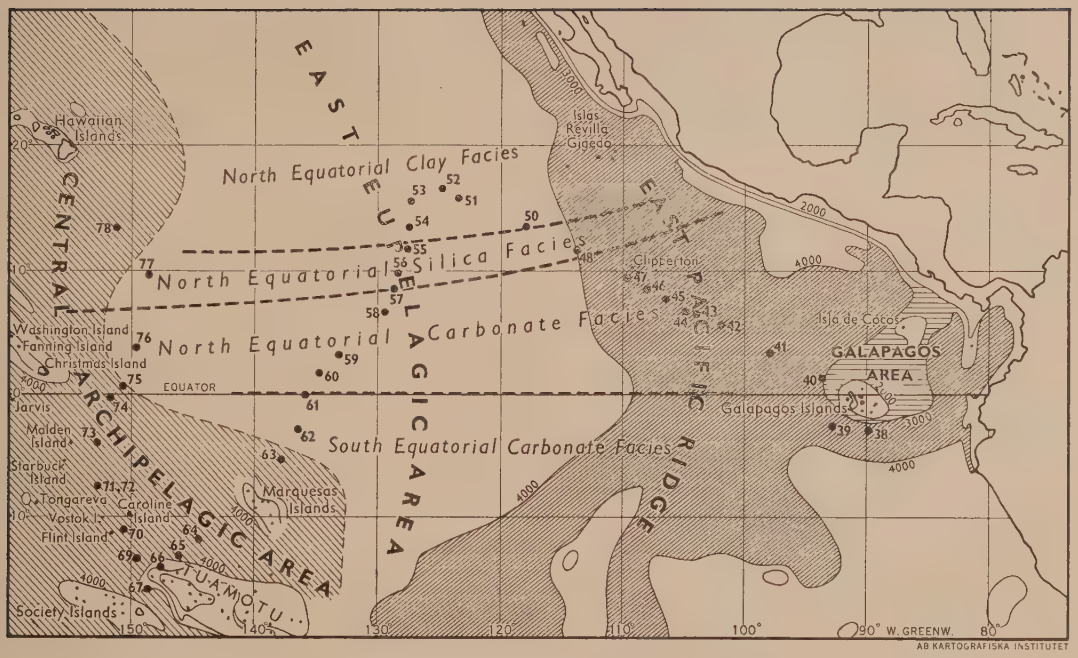

Fig. 3.0. Location of cores and environmental subdivision of the East Equatorial Pacific.

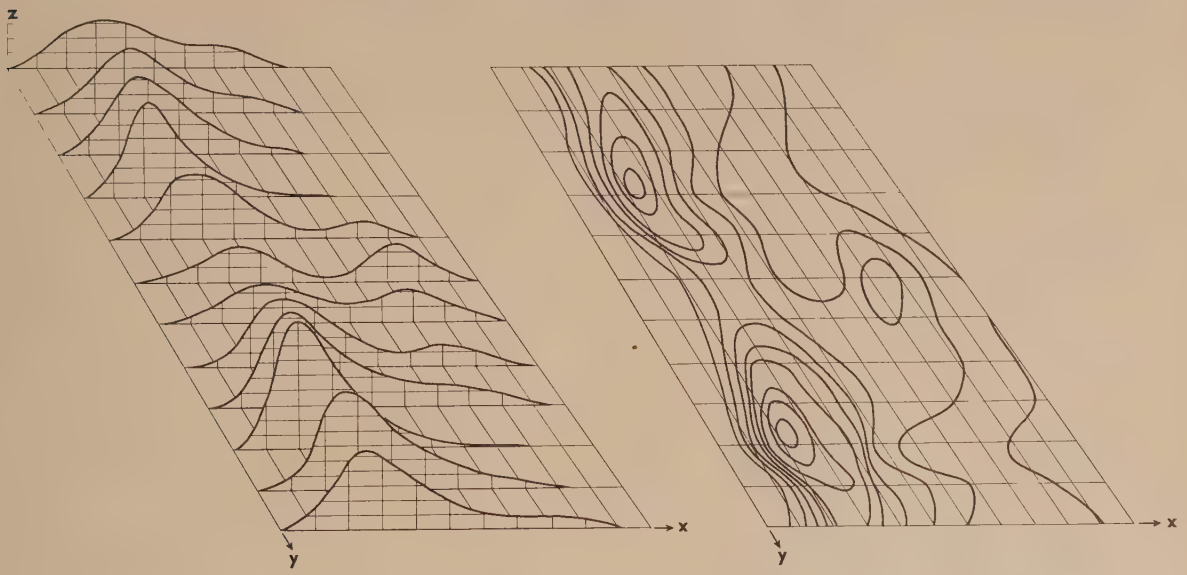

Fig. 1.0.3. Illustration of the transformation of frequency (z) distribution of a property (x) as a function of another property (y) to an isoplethic diagram.

taken as 1 *for*, this unit being equal to 1 mg per cm^2 in 1 000 years (§ 1.2.9).

The *rac of lutite* in the eupelagic Pleistocene deposits has been calculated to be 73 fors (§ 1.2.10).

The *eupelagic environment* is defined by constancy of the rate of lutite deposition and accumulation.

In indicating *concentrations* the chemical formula of the element or compound in question is used to indicate absolute concentration. $CaCO_3 = 487 \cdot 10^{-3}$ or $CaCO_3 \cdot 10^3 = 487$ thus means that the concentration of calcium carbonate is 0.487 (48.7 %).

The *content of titanium in the eupelagic lutite* corresponds to $733 \cdot 10^{-5}$ TiO_2 (§ 1.2.10).

1.0.3 Diagrams.

A few types of graphs may require comment. The stratigraphical diagrams (pl. 2.38—2.62) are provided with a separate explanation.

Isoplethic diagrams of two slightly different types occur in this work. The first type is used to demonstrate size distribution as a function of depth in the sediment (fig. 1.9.2.4 pl. 2.59—2.61, col *Coscinodiscus nodulifer*, fig. 2.62.9). The process of construction is seen from fig. 1.0.3. For each level investigated the size frequency distribution curve has been constructed, the size being plotted on the x-axis and the frequency within the size classes on the z-axis. These distributions have been arranged along the y-axis, which indicates the depth in the sediment. By interpolation of an infinite number of distributions between the stratigraphical levels investigated a distribution body is formed. The intersection lines between the surface of this body and the z-values 1, 5, 10, 20, 30 and 40 % form equiprobability curves or isopleths, which have been projected vertically on the x—y-plane (right part of fig. 1.0.3). This projection constitutes the isoplethic diagram used.

The same type of graph has been used to demonstrate the frequency (z) distribution of properties (x) as a function of geographical latitude (y), e. g. in fig. 1.4.2.1 and 1.4.2.2. In both types the ordinates of the populations analyzed have been indicated by a grid line. The vertical grid lines usually indicate the class interval.

TABLE 1.0.3

Lower class limits in logarithmic grouping systems, suitable for the analysis of pelagic sediments.

Group no.	System 4	System 10	System 20
1	142	2	1
2	156	3	2
3	171	4	3
4	187	5	4
5	205	6	6
6	225	8	9
7	246	10	14
8	270	13	22
9	296	16	36
10	324	20	56
11	355	25	89
12	390	32	142
13	427	40	224
14	468	50	355
15	513	63	563
16	563	80	892
17	617	100	1 413
18	677	126	2 239
19	742	159	3 548
20	813	200	5 624
21	892	252	8 913
22	978	317	14 125
23		399	22 388
24		502	35 482
25		632	56 235
26		795	89 126
27		1 000	141 254
28		1 260	
29		1 586	

A similar diagram has been used to illustrate the correlation between two properties, e. g. calcium carbonate concentration and salinity (fig. 1.12.2.1 and 1.12.2.2). As a first step in the preparation of these correlation diagrams the material was divided in carbonate concentration classes, with a class interval of 5 % $CaCO_3$. Thus class 1 comprises all samples with a carbonate content of 0—4.9 %, class 2 samples with 5—9.9 %, a. s. o. These class intervals are indicated by the horizontal grid lines of the diagrams. Each carbonate class was then subdivided in salinity classes with an interval of 1 % Sal, indicated by the vertical grid lines. Each carbonate class (horizontal array of squares in the diagram) was regarded as a separate population and the sample frequency within each salinity class of these (each square) was calculated as the percentage of the total number of samples in the carbonate class. The distribution is thus known from square to square but not within these. The standard deviation of the frequency values is dependent on the total number of samples in each major (in this case = carbonate) class. In order to illustrate the relative significance of the frequency values, the number of samples in the major classes has been indicated in a graph to the right of the correlation diagram. In the curve of this graph the abscissae of the class centres indicate the sample number in question on a logarithmic scale. The construction of the isopleths was carried out as indicated above.

In several cases the analysis values are logarithmically distributed and in order to keep the significance of the frequency values as uniform as possible over the entire distribution body, a logarithmic grouping was applied instead of an arithmetic one. Examples of this type of distribution are given in fig. 1.4.3.4, 1.5.4.2, and 1.7.2.2, where both major and minor groups are logarithmic. An example of a distribution where the major grouping is logarithmic and the minor grouping is arithmetic is given in fig. 1.7.2.1. The logarithmic grouping systems most frequently used are summarized in table 1.0.3. System no. 4 with an interlogarithmic class interval of 0.04 was applied to the grouping of calcium carbonate values in calcareous sediments. System 10 with the log interval 0.10 was found to be suitable for the grouping of concentrations of all trace constituents, such as C, N, P_2O_5 and TiO_2, and of rate of accumulation in most cases. In cases where great differences occur between the maximum and minimum values of rate of accumulation, e. g. in rac $CaCO_3$, system 20 was applied. This was also generally used for microfossil concentration grouping.

The correlation diagrams shown in part 2 are prepared according to the same grouping procedure as described above, but because of the low number of samples in the populations, the isopleths have been omitted and the number of samples is indicated by points. The location of these within the squares is in most cases not determined.

The frequency distribution diagrams, e. g. fig. 1.5.2.1 and fig. 1.10.2.1 were prepared in the same way as the major group distributions of the isoplethic diagrams.

Most of the bottom profiles, shown in fig. 2.38.0—2.62.0, were kindly placed at the author's disposal by Dr. F. Koczy. The echo depth indicated in these graphs is not corrected with regard to the regional hydrographical conditions. The corrections amount in the area in question to appr. +0.12, 0.24, and 0.23 % of the depths 4 400, 4 600, and 4 800 m.

The synoptic stratigraphical profiles (e. g. fig. 1.1.5) are based on the vertical distribution of properties found in the sediment cores. The distribution in the areas between the cores is interpolated.

1.0.4 Classification of pelagic deposits.

In the present work the classification proposed by REVELLE (o. c, p. 16) has been used with some minor modifications.

A. *Oozes.* Skeletal remains of organisms dominate the sediment.

Remark: Proportion of skeletal remains should be determined chemically.

1. *Calcareous oozes.* The sediment is dominated by $CaCO_3$. *Remark:* All sediments with $CaCO_3 > 50$ % are thus calcareous oozes, and likewise e. g. a deposit consisting of 40 % $CaCO_3$, 30 % biogenous silica and 30 % clay, but not e. g. a deposit consisting of 35 % $CaCO_3$, 40 % biogenous silica and 25 % clay which must be designated siliceous ooze.

   a. *Chalk ooze.* $CaCO_3 > 60$ %. *Remark:* Subdivision of REVELLE's calcium carbonate ooze appears advantageous from a stratigraphical point of view. The term chalk ooze is suggested because of the petrographical agreement of this type of deposit with the chalk, as defined e. g. by PETTIJOHN (1949, p. 299).

   b. *Marl ooze.* Calcareous ooze with $CaCO_3 < 60$ %.

   a and b are further subdivided with regard to the dominating fossil groups in the carbonate component into *foraminiferal*, *coccolith* and *pteropode ooze.* The foraminiferal oozes might be further subdivided with regard to the dominating genus. In the East Pacific, *globigerina* and *globorotalia chalk and marl oozes* and *sphaeroidinella marl ooze* are of importance. These types are stratigraphically significant. With regard to the nature of the non-calcareous matter the marl oozes (and possibly the chalk oozes) should be divided into *argillaceous*, *volcanic*, *detrital*, *siliceous* or *ferruginous* when clay, volcanic debris, detrital minerals or biogenous silica dominate the non-calcareous component, or when large amounts of oxidates occur. *Remark:* The quantitative definition of ferruginous pelagic deposits should be postponed until an extensive statistical material of manganese and iron analyses is available.

2. *Siliceous oozes.* The sediment is dominated by biogenous silica.

   a. *Radiolarian ooze.* The biogenous silica is dominated by radiolaria.

   b. *Diatom ooze.*

   c. *Colloidal siliceous ooze.* The dominant part of the biogenous silica has been peptized and is present as silica gel.

In accordance with the subdivision of calcareous oozes the siliceous oozes might be designated *argillaceous*, *volcanic*, *detrital*, *calcareous* or *ferruginous*.

Remark: The concentration of biogenous silica should be estimated by chemical methods if possible.

B. *Pelagic clay.* The sediment is dominated by lutite (KUENEN, 1950, p. 347). Subdivision in accordance with groups A 1 and 2 in *calcareous*, *siliceous*, *volcanic*, *detrital* or *ferruginous* pelagic clay. *Remark:* The term »red clay» is regarded as inadequate and misleading as the pelagic clays appear to be whitish or yellowish grey under depositionally normal conditions (e. g. the Pleistocene eupelagic clay series in the North Equatorial Pacific). From a depositional point of view the dark reddish and brownish colours are regarded as abnormal and as indicating the presence of great amounts of halmyrogenous or minerolytic oxidates (cf. § 1.12.6). The term *red clay* in its restricted sense corresponds to the proposed term *ferruginous pelagic clay*, which may be the type with the widest areal distribution.

1.1 Calcium carbonate

1.1.1 Origin and nature of carbonates.

Microscopical investigations of the material have shown that the calcium carbonate is present mainly in the form of skeletal remains of foraminifera and coccolithophoridae and as minute grains of uncertain origin. The total concentration of carbonates in the deposit, expressed as calcium carbonate, and the concentration of foraminiferal remains $> 150\ \mu$ in terms of number per weight unit of the sediment have been determined quantitatively. The relationships between concentration of carbonates and concentration of foraminifera are treated in chapter 1.7. Other calcareous structures represented in the material in accessory amounts only are pteropode shells, fragments of other unidentified mollusc shells, otoliths and in a few cases small nodules with calcium carbonate as cementing matter. No attempt has been made to estimate the concentration of carbonates other than calcium carbonate and the total amount of carbonate determined analytically has been accounted for as calcium carbonate. REVELLE (1944) investigating Pacific calcareous oozes found practically no magnesium carbonate.

No studies have been carried out with regard to the mineral form of the calcium carbonate. REVELLE (o. c.) states that aragonite is not present in Pacific calcareous oozes and the carbonate should thus be present only as calcite.

Recrystallization of the carbonate is frequent and is dealt with further in § 1.12.6.

1.1.2 Factors determining the concentration of calcium carbonate.[1])

The analytical results are reported as parts per thousand of calcium carbonate in salt-free sediment, dried at 10.5 T_{H_2O} and 20° C (cf. chapter 4.7). This concentration depends on the rate of accumulation of calcium carbonate and the rate of accumulation of noncalcareous matter (mainly minerogenous matter and biogenous silica). The total rate of calcium carbonate accumulation (A) is in its turn determined by the rate of production of calcareous plankton (p_p), the rate of benthonic carbonate production (p_b), the rate of precipitation of calcium carbonate within the sediment (p_i), the rate of dissolution of planktonic calcareous structures during settling (d_s), the rate of dissolution after deposition and before burial beneath the

[1]) A survey of these relationships is given by SVERDRUP e. a, o. c, p. 997—1008. The following paragraph is based on this survey and the literature quoted in it and is completed, modified or altered according to the results of the present investigation.

zone of burrowing (d_b) and the rate of posthume[1]) dissolution (d_i). Thus

$$A = p_p + p_b + p_i - (d_s + d_b + d_i)$$

To judge from the observations made in the present material p_i and d_i appear to be negligible, except in cases where the subsurface content of organic matter is high or where metasomatic solutions are active (both cases represented in the East Pacific Ridge sediments ch. 2.38—2.47). In the eupelagic environment the net rate of carbonate accumulation thus depends on the rate of deposition of organic calcareous remains ($p_p + p_b - d_s$) and on the postdepositional rate of dissolution before definite burial (d_b).

As far as the East Eupelagic carbonate area (core 58—62) is concerned the water depth on the stations is constant within 4.5 %, and the deep water body can be regarded as laterally homogenous. The rate of dissolution during settling (d_s) is therefore believed at a given time to be constant over the area in question. The main components of the postdepositional, prehume carbonate dissolution (d_b) are believed to be 1) the dissolution caused by the contact of the solid carbonate with sea water, unsaturated with regard to calcium carbonate (d_{b_i}), and 2) dissolution caused by carbonic acid produced through the metabolism of bottom living organisms, many of which repeatedly churn over the sediment and pass it through their alimentary tracts (d_{b_o}) (REVELLE o. c.). As was indicated by CORRENS (o. c.), the magnitude of d_{b_i} depends, at constant depth, foremost on the temperature, salinity, alkalinity, and rate of renewal of the bottom water. The resultant of these properties might be collected under the term *aggressiveness*. Another factor should be added to those enumerated, viz. the influence of the rate of deposition of non-calcareous matter. In two localities with different rates all other factors being equal, d_{b_i} will be greater where this rate is lower as the sediment surface exposed to dissolution, consists to a greater percentage of calcium carbonate in the latter case. In a region of eupelagic deposition such as the East Pacific Eupelagic area (fig. 1.0, at the end of this part), where at a given time the rate of dissolution during settling (d_s) and the properties of the bottom water may be regarded as constant[1]) the rate of dissolution will thus be greater in those environments where the rate of deposition of biogenous silica is small.

The factor d_{b_o} might be expected to be greater where the supply of nutrients is high, i. e. in areas with a high rate of biogenous accumulation (REVELLE, o. c). This factor might contribute to the general decrease of the calcium carbonate content in the East Pacific Ridge deposits which are comparatively rich in organic matter (ch. 1.4 and 2.38—2.48) but is apparently of smaller magnitude than the carbonate deposition factor ($p_p + p_b - d_s$) and the factor d_{b_i}.

The measured concentrations can be transformed to rates of accumulation (rac) in the cases where the time factor is known (ch. 1.2). In such cases the rac is expressed in the unit for (1 for = 1 mg/cm² · 1 000 years). No method has been found to estimate quantitatively the rate of dissolution (*rd*). Qualitatively the *rd* of calcium carbonate can be estimated through studies of etching structures in coccoliths and foraminiferal tests. (ch. 1.12)

1.1..3 Present distribution of calcium carbonate.

In his report on the bottom samples collected by the »Carnegie» from the Pacific, REVELLE

[1]) The suggested terms prehume and posthume refer to processes taking place before and after the burial of the sediment below the zone of burrowing.

[1]) If the rate of circulation of the water were small in comparison with the rate of dissolution, marked regional differences in the alkalinity would arise. The fact that the complete renewal of the deep water appears to be a matter of a few hundred years (KULP, FEELY and TRYON (1951)) and that the Pacific deep water samples of the Swedish Deep Sea Expedition, do not display great variations in pH and alkalinity (F. Koczy, personal communication), however, make it probable that marked regional differences in the aggressiveness of the bottom water do not occur over the East Eupelagic section from 3° S to 7° N.

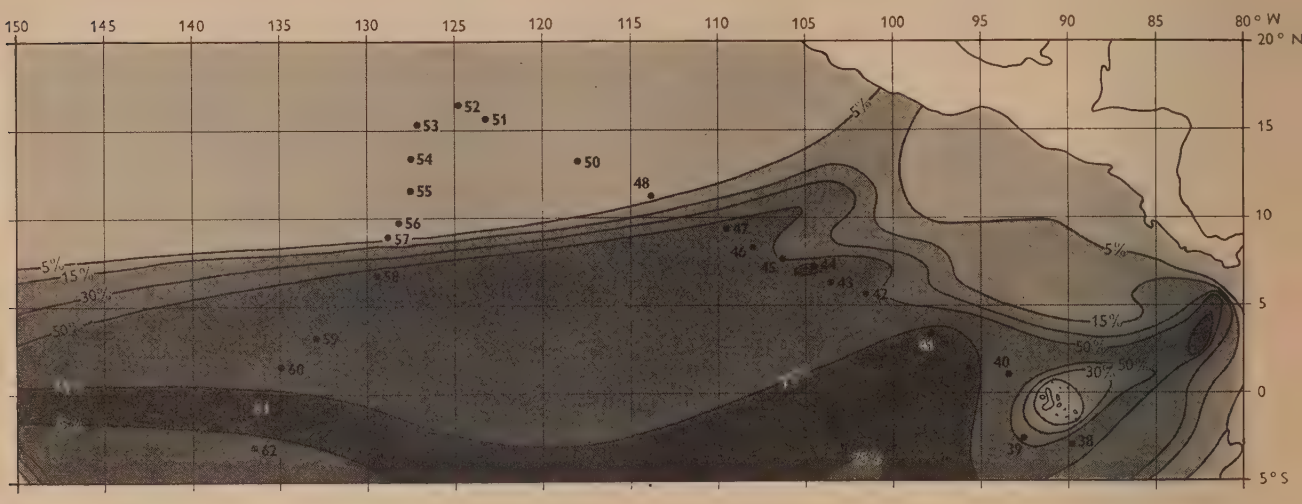

Fig. 1.1.3.1. Distribution of calcium carbonate in the surface sediments of the East Equatorial Pacific, according to SCHOTT (o. c.), REVELLE (o. c.) and the present results.

(1944) has published a chart of the areal distribution of calcium carbonate, based upon the Carnegie results and other available analyses. Another map, based on available data, was published by W. SCHOTT in G. SCHOTT (1934, pl. V).

These charts have been modified in accordance with the results gained by the present investigation, the revised distribution being shown in fig. 1.1.3.1. The most important of the features revealed by the new material is the still more marked parallelism between the carbonate distribution pattern and that of the surface current distribution. This relationship was first indicated by MURRAY and RENARD (1891, p. 178) and was further stressed by REVELLE (o. c., p. 103). The East section through the East Pacific sampled by the Swedish Deep Sea Expedition demonstrates that the belt of calcareous ooze swings up towards the Middle American coast, ending in an irregular pattern. In this part of the ocean the Equatorial Counter Current is known to behave in a similar way (JERLOV, vol. III) sending a branch to the northeast and dissolving in a series of vortices. A detailed agreement between the rate of production of carbonates at the surface of the ocean and the percentage of carbonates in the bottom deposit can, however, not be expected in this East section as it runs over the East Pacific Ridge where extensive regional discrepancies exist in the rate of minerogenous accumulation (see chapters 2.40—2.47).

Additional evidence has also been acquired with regard to the carbonate distribution in the Galapagos area, although the sample frequency in this area is regarded as not yet high enough to reveal the details of the relationships with the hydrographical conditions. These are here complicated, due to the interaction of the Peru current and the Equatorial Counter Current (cf. JERLOV o. c.). A feature which can also be seen from REVELLE's chart is the high carbonate content of the deposit SE of the Galapagos Islands and the comparatively low content to the SW. The hydrographical work of the expedition referred to above and now under preparation might explain this distribution.

The most interesting section over the East Equatorial Pacific facies boundaries is the one running from 16° 35′ N, 124° 48′ W (core 52) to 3° 00′ S, 136° 26′ W (core 62). In this region, the East Eupelagic area, the rate of minerogenous accumulation has been demon-

strated to be very uniform (ch. 1.2), the bottom topography is favourable and according to a personal communication from Dr. Jerlov the hydrographical conditions are clearly defined, the Equatorial Counter Current and the divergences and convergence of the Equatorial Current System being very well developed.

Fig. 1.1.3.2 shows schematically a meridional section through the surface layer of the ocean with the currents indicated by arrows (redrawn from SVERDRUP e. a, o. c). Below this diagram is indicated the carbonate content of the Recent deposit as inferred from the sediment cores. The real surface is represented only in cores 55, 57 B, 58, and 61. In cores 52, 54 and 56 the material coating the upper part of the core was, however, free from carbonates, which makes certain that no calcareous sediment is now deposited at these localities. In cores 59, 60, and 62 the order of magnitude of the Recent concentration of carbonate has been judged from the content found in the tops of the cores, representing Subrecent. In core 60 this Intermediate Postglacial content is only a few percent above the marl-chalk ooze limit (60 %) and the Recent deposit might possibly touch or pass slightly below this limit. This is partly due to the high rate of accumulation of biogenous silica, which dilutes the carbonate. The concentration of calcium carbonate at the real surface of core 62 is not known, as a comparatively thick top layer is missing (appr. 50 cm) and the lime content can, therefore, not be estimated from the conditions in the present top of the core (presumably Late Glacial). From fig. 1.1.5 is seen, however, that the average rate of Pleistocene accumulation is somewhat lower than in the cores 59 and 60. In accordance therewith it is believed also that the Recent rate of calcium carbonate accumulation is probably slightly lower in core 62 than in 59 and 60.

The main features evident from fig. 1.1.3.2 are the absence of calcium carbonate from the area below and north of the North Equatorial Divergence (D_1), the rapid increase in percentage below the Equatorial Counter Current (E) and the very high carbonate concentration below the Equatorial Divergence (D_2).

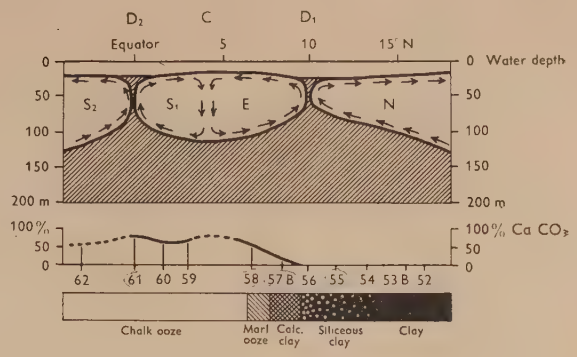

Fig. 1.1.3.2. Relation between surface currents and present composition of the sediment. The upper graph shows a generalized section through the Equatorial Current System (redrawn from Sverdrup e. a, o. c.). The lower diagrams illustrate the composition of the sediment and the location of the cores 52—62. D_1 and D_2, North Equatorial and Equatorial Divergence; C, Equatorial Convergence; N, North Equatorial Current, S_1 and S_2 northern and southern cells of South Equatorial Current; E, Equatorial Counter Current.

1.1.4 Interpretation of the present eupelagic distribution of calcium carbonate.

MURRAY and RENARD (o. c.) have already pointed out that the production of foraminifera increases considerably in the Counter Current and that this might be the reason for the close agreement between the average path of the current and the facies boundary. This certainly is the correct explanation of the main features of the carbonate distribution but gives no clue to the details.

Already north of the North Equatorial Divergence an increased rate of biogenous production is indicated by the increased content of biogenous silica in the deposit. The rate of production of calcareous skeletons is certainly also increased but not enough to outweigh the rate of dissolution. Below or slightly south of the North Equatorial Divergence the line is passed (cf. fig. 1.1.3.2) where the rate of deposition ($p_p + p_b - d_s$) is equal to the rate of postdepositional dissolution (d_b). This is defined as the *compensation line*.

Further to the west (160—170° W), where the rate of upwelling, the productivity, and therefore also the rate of deposition of calcium carbonate decreases, the compensation line bends to the south over the Equator and passes back to the east in the South Pacific. This is evident e. g. from REVELLE's and SCHOTT's maps (o. c.). A factor, which is believed to be important for the distribution of calcium carbonate below the Equatorial Current system, is the meridional transport. GRAHAM (1941) has shown that the production of phytoplankton is considerably higher in the divergences (D_1 and D_2 in fig. 1.1.3.2.) than in the Equatorial Counter Current, this being due to the abundant supply of nutrients in the divergences. In spite of this, the compensation line is situated below the North Equatorial Divergence (D_1). This may be explained by JERLOV's investigations (vol. III of this Report) of the particle distribution in this section of the sea. JERLOV's results indicate that much of the plankton produced in D_1 is carried to the south and deposited on the way to or in the convergence, C.

The results of the investigations of the bottom deposits make it clear that the rate of deposition is much higher below the Equatorial Divergence (D_2) than below the North Equatorial Divergence (D_1).

It is, however, difficult to judge the magnitude of this difference by estimating the rate of deposition of calcium carbonate below the divergences, because of the above mentioned possibility of meridional transport, and as the rate of deposition of calcium carbonate is surpassed by the rate of dissolution below the North Equatorial Divergence.

1.1.5 Stratigraphical distribution of calcium carbonate.

The details of the stratigraphical distribution of calcium carbonate in the eupelagic environment are shown in pl. 2.52—2.62 (present North Equatorial carbonate facies, pl. 2.58—2.62) and on the East Pacific Ridge in pl. 2.39, 2.42, 2.45 and 2.46, col. $CaCO_3$. A synoptical profile diagram based on these distributions has been prepared in fig. 1.1.5. The right part of this demonstrates a section through the deposits of the East Eupelagic area from 7° N to 3° S (latitude indicated on the x-axis). The ordinates are the depths in the sediment from the present sediment surface. The sediment cores are indicated by vertical lines and the core numbers are inserted below these. Clay (< 30 % $CaCO_3$) is indicated with black tone, marl ooze (30—60 % $CaCO_3$) shaded, and chalk ooze (> 60 % $CaCO_3$) with light tone. The distribution in the areas between the cores is interpolated. The correlation of the strata is based on the agreement between the curves of calcium carbonate concentration and rac in the different cores (cf. below and ch. 3.3), in some levels on the size distribution of *Coscinodiscus nodulifer* (ch. 1.9) and on the titanium age determination, (cf. ch. 1.2, and § 2.58.13—2.62.13). The details of the vertical distribution of calcium carbonate are discussed in chapters 2.58—2.62, § 1, and in part 3.

Due to the regional differences in the rate of production and accumulation of calcium carbonate and biogenous silica (cf § 1.1.3) the strata dip towards the Equator, where the rate of accumulation reaches its maximum below the Equatorial Divergence.

A prominent feature in fig. 1.1.5 and in pl. 2.58—2.62, col. $CaCO_3$, is the beautifully developed stratification with regard to calcium carbonate. Post Glacial and Recent (stage 1) are apparently characterized by a reduced rate of calcium carbonate accumulation. This is demonstrated by cores 58 B and 61 B (pl. 2.58 B and 2.61 B), which include Recent, as well as by the trend of the carbonate concentration and rate of accumulation in the truncated tops of cores 59 and 60.[1]) In core 58 B the

[1]) Owing to its great total length core 62 has been truncated down to Early Post Glacial and the concentration at the real top cannot be extrapolated.

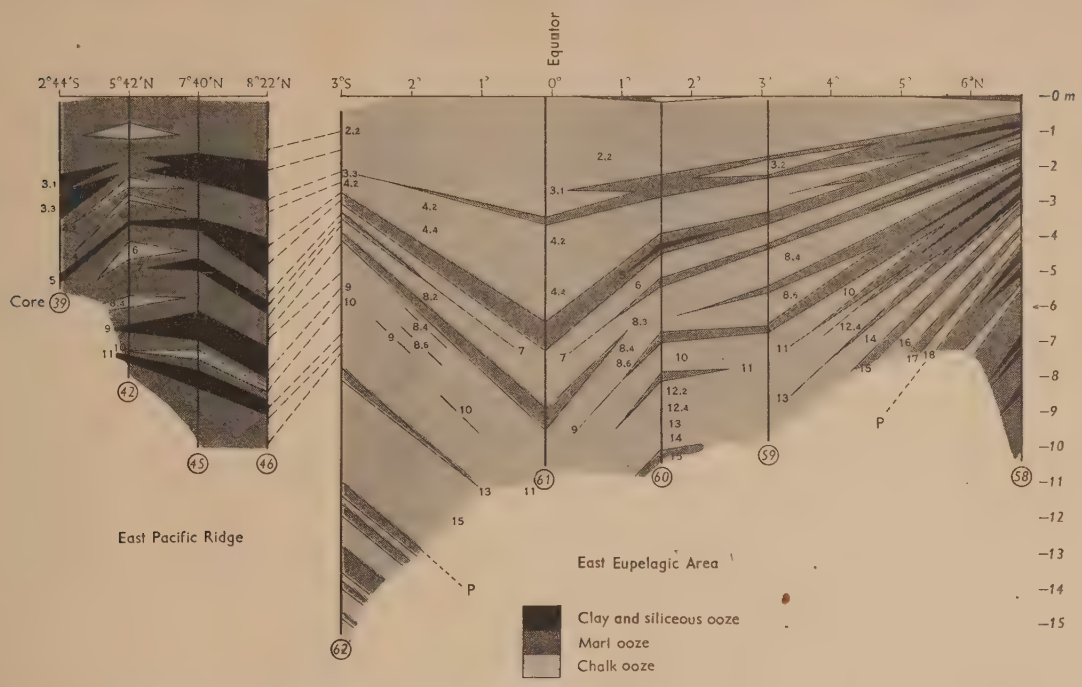

Fig. 1.1.5. Distribution of calcium carbonate in North-South sections through the East Pacific carbonate area. The intersection with the present sediment surface is idealized to a horizontal, straight line. Stage and substage centers are indicated by labelled lines. P indicates the suggested Pliocene-Pleistocene boundary.

rate of accumulation is too low to allow a division of Post Glacial (stage 1) into substages. For this purpose core 61 B is, however, well suited. From pl. 2.61 B, col. $CaCO_3$, dashed curve, is seen that there is a Post Glacial minimum in the rate of accumulation (substage 1.3), which is still lower than the Recent one. This minimum is followed by an accumulation maximum (substage 1.2) directly underlying Recent (substage 1.1). The radiocarbon-titanium age determinations indicate that the culmination of subage 1.3 occurred appr. 9 000 years ago and that subage 1.2 extended from — 4 300 to — 3 100 The dating of these events should, however, be regarded as preliminary as long as it has been carried out in one core only. Below the comparatively carbonate-poor Recent and Post Glacial strata, which, according to the titanium-radiocarbon age determination (ARRHENIUS, KJELLBERG and LIBBY, 1951) correspond to appr. 17 000 years (level — 15 cm in core 61), follows stage 2 with a very strongly increased rate of accumulation of lime and with several subordinate maxima (fig. 1.1.5, 1.1.6.1, pl. 2.58—2.62). This stage extends back in time appr. 70 000 years and is preceded by a low-accumulation stage (3) with an approximate age of the lower boundary of 150 000 years. Within stage 3 there is a subordinate maximum of rate of carbonate accumulation and of carbonate concentration (substage 3.2).

Stage 3 rests upon another group of strata with a high calcium carbonate concentration and a high rate of carbonate accumulation (stage 4 with substages .2, .3, and .4), together comprising appr. 82 000 years. This alternation between carbonate-rich and carbonate-poor strata continues backwards in time with decreasing concentration amplitudes of fluctuation and increasing average carbonate content.[1]) Cores 59 and 60 penetrate stage 14 (appr. 750 000

[1]) The stratigraphical subdivision of this series is treated in part 3.

years) and core 61 does not reach further back than to stage 9 (approx 510 000 years). Core 62, on the other hand, which is nearly 15 m long, and core 58 which is located in an area of a low rate of biogenous accumulation, reach down to strata respectively 1.6 and 2.5 million years old (extrapolated age values). Marked changes in the carbonate concentration occur also in these lower beds, especially above stage 18 (appr. age 1 million years). This is regarded as the first main stage of the Pleistocene series (cf part 3). The scarcity of traces of dissolution in foraminiferal tests in the lower Pleistocene and especially in the Tertiary indicates that the rate of dissolution has been low and that the comparatively high rates of accumulation of calcium carbonate are due to this rather than to a high rate of deposition of carbonate.

The left part of fig. 1.1.5 shows the calcium carbonate stratification in the correlatable East Pacific Ridge cores (cf. ch. 2.38, 2.42, 2.45, and 2.46). In this area the rate of minerogenous accumulation is high and varying and the carbonate concentrations are low in spite of the high total rates of accumulation. To judge from the frequent traces of far-reaching dissolution of foraminifera in the carbonate minima, the rate of calcium carbonate dissolution is comparatively high in this area. This is believed to be due to the high content of organic matter in the sediment (ch. 1.4) which presumably gives rise to carbonic acid, dissolving the calcareous structures.

In some instances locally abraded sequences have been sampled in the area north of the present calcium carbonate compensation line. These sequences (cores 53, 56, and 57) display the interesting fact that in Tertiary time, accumulation of calcareous sediments took place in this area and that the change to the present clay and silica facies type occurred much earlier than the beginning of the Pleistocene (ch. 2.53, 2.56, 2.57 and part 3).

1.1.6 Interpretation of the eupelagic stratigraphical distribution of calcium carbonate.

Summary of facts. As pointed out in § 1.1.2, the main factors influencing the rate of calcium carbonate accumulation in the East Pacific Eupelagic Area are 1), the rate of production of calcareous matter ($p_p + p_b$), and 2), the rate of dissolution during settling (d_s) and before definite burial (d_b) which are both influenced foremost by the temperature, alkalinity and rate of circulation of the water and the latter also by the rate of deposition of non-calcareous matter = rdep biogenous SiO_2 (varying in a similar way as rdep $CaCO_3$) + rdep minerogenous matter (appr. constant in the eupelagic environment).

The high rate of accumulation of $CaCO_3$ found below parts of the Equatorial Current System is indirectly due to the high rate of production of phytoplankton at the surface of the ocean. This high rate of production is known to depend on the extensive supply of nutrients to the euphotic layer made possible by the upwelling in the divergences. (Sverdrup e. a, o. c.). The highest present and Upper Pleistocene average rates of carbonate accumulation are found below the Equatorial Divergence. The rate of calcium carbonate accumulation has been subject to extensive changes with time (fig. 1.1.6.1), and these changes are more marked in the Pleistocene than in the Tertiary and most pronounced in the Upper Pleistocene. As far as can be controlled by means of available methods of dating, the culminations of the change in rac of calcium carbonate are isochronous throughout the East Eupelagic Area. The present time is a time of comparatively low rac $CaCO_3$ and this rate is strongly increased in the strata which are believed to be isochronous with the Last Glaciation in higher latitudes.

Interpretation. During the Ice Ages the rate of circulation of the deep water is likely to have been increased and the ability of the water to dissolve calcium carbonate thus probably was great. In spite of this the rac $CaCO_3$ was con-

siderably increased in the East Eupelagic Area during the last Ice Age. This indicates that the rate of production of carbonate was increased to a far higher degree than the rate of dissolution $\left(\left|\frac{\partial (p_p + p_b)}{\partial t}\right| \geqq \left|\frac{\partial (d_s + d_b)}{\partial t}\right|\right)$.[1] The reason for the increased production of calcium carbonate (foraminifera and coccoliths) is believed to be an intensified production of phytoplankton due to an increased rate of upwelling in the divergences. As pointed out in an earlier paper (ARRHENIUS 1950), a high rate of upwelling may indicate an increased speed of the Equatorial Counter Current and of the North and South Equatorial Currents. In any case the high rate of upwelling very probably reflects a reinforcement of the trade wind intensity and thus of the atmospheric circulation in low and intermediate latitudes. An investigation of the meteorological implications has been carried out by NYBERG (vol. V part 5).

In analogy with the fact that the stages 1 and 2 correspond to the Postglacial and the Last Ice Age, stage 3 is believed to correspond to the Last and stage 5 to the Penultimate Interglacial and stage 4 to the Penultimate Ice Age. This hypothesis is further extended to all preceding time-rock units, the even-number stages corresponding to ages with an increased and the odd number to ages with a decreased intensity of vertical circulation. The hypothesis does not necessarily demand a detailed agreement between the low latitude circulation changes and the climatic events recorded in the high latitudes of the continents. The latter are certainly influenced by secondary local or regional meteorological complications brought about by the distribution of ice sheets and by topographical, hydrographical, and other factors (ZEUNER 1945, FLINT 1948). It should be stressed, that although the duration of the stages can be estimated from their titanium content, the corresponding relative or absolute magnitude of the rate of production and circulation cannot be derived from the calcium carbonate concentration or rate of accumulation relationships. The reason for this is that the rate of accumulation of calcium carbonate is determined not only by the rate of production but also by the rate of dissolution (§ 1.1.2). When the maximum rac $CaCO_3$ of e. g. stage 4 is lower than the corresponding value of stage 10, this means either that the rate of production was higher in 10 than in 4 or that the rate of dissolution was lower. This is assumed to give the clue to a feature of the stratigraphical calcium carbonate distribution, which might at first appear puzzling. From fig. 1.1.6.1, pl. 2.58 and 2.62, and from pl. 2.59—2.60, it is seen that the maximum conc. $CaCO_3$ and rac $CaCO_3$ is high in the Lower Pleistocene ages of increased rate of circulation in comparison with the corresponding Upper Pleistocene ages. Further, comparatively high carbonate peaks occur also in the Pliocene. These conditions have been indicated schematically in fig. 1.1.6.2. With regard to what is known about the Pliocene-Pleistocene climatic evolution in higher latitudes this distribution might at first appear paradoxical.

A hypothetical explanation of these distribution features is indicated in fig. 1.1.6.3, where the lower diagram illustrates the assumed type of changes of the rate of dissolution of calcium carbonate with the rate of circulation. The intermediate graph shows the assumed type of corresponding changes in the rate of production of calcium carbonate and the upper one demonstrates the inferred type of functional relationship between the observed rate of accumulation and the assumed rate of circulation. The graphs are only intended to illustrate qualitatively the hypothesis put forth here.

As was indicated in § 1.1.2 the magnitude of rd $CaCO_3$ (lower diagram in fig. 1.1.6.3) depends principally on the aggressiveness of the water in the column which the particles have to pass on their way to the bottom and

[1] Assuming contemporaneous inflexions in the functions of p and d.

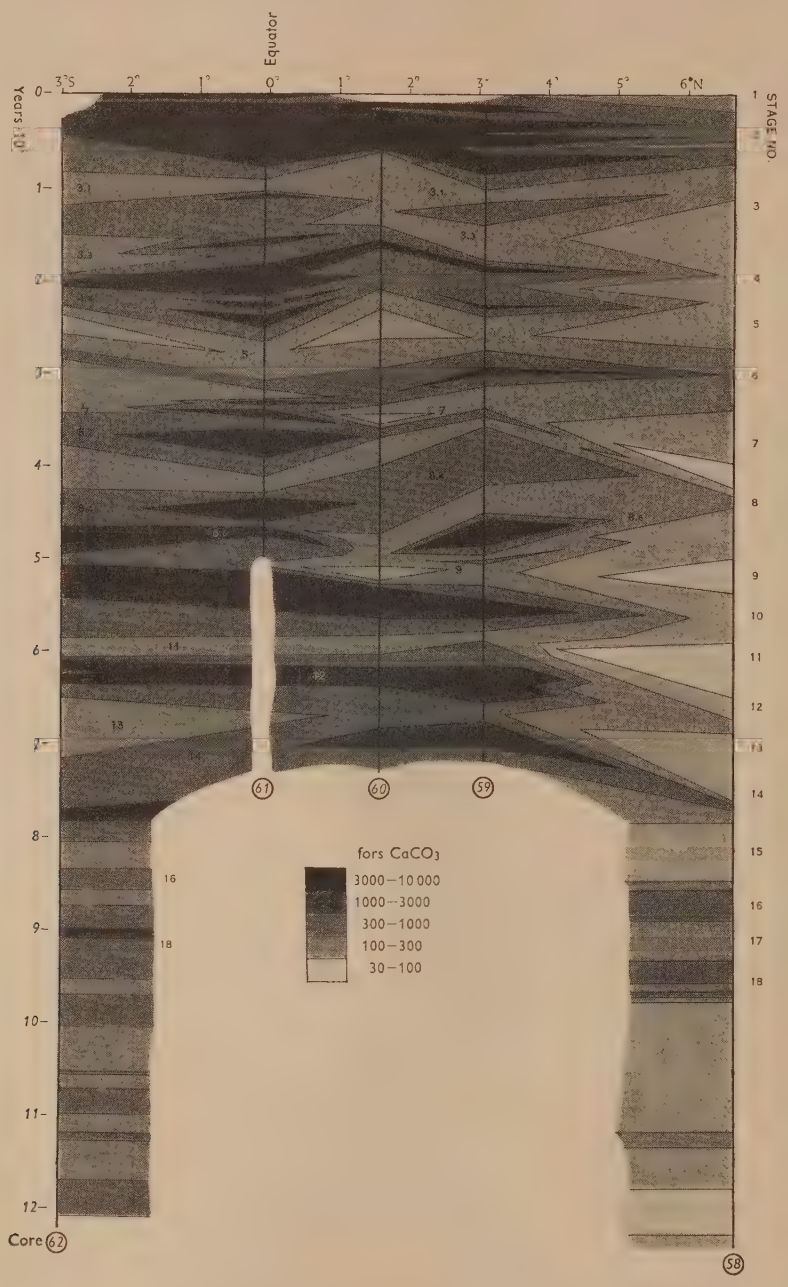

Fig. 1.1.6.1. Pleistocene and Upper Pliocene rate of accumulation of calcium carbonate as recorded by the East Eupelagic carbonate sequences. The sediment cores are indicated by vertical lines. The core number is indicated below the line and the geographical latitude is seen from the horizontal scale. The vertical scale to the left indicates the titanium age expressed in years: 10^5. The figures to the right and within the diagram are the stage and substage numbers. The shades show the rates of accumulation expressed in fors, 1 for being equal to 1 mg/cm² · 1 000 years. If there were no analytical errors in the determination of titanium and specific gravity, if the samples analyzed were fully representative of the intervening sediment layers, if the culminations of the decrease or increase in rate of accumulation were synchronous throughout the section, if the rate of minerogenous sedimentation were constant or changing uniformly over the section, and if the concentration of titanium were exactly proportional to the concentration of minerogenous matter; then corresponding maxima and minima of rac $CaCO_3$ would have exactly the same titanium age in all cores. The deviations in titanium age, believed mainly to be caused by the first and second sources of error indicated above, are thus illustrated by the dip of the centers of the strata in the diagram. With regard to the radiocarbon — titanium age determination, s. f. ch. 1.2, § 2.58.13—2.62.13 and Arrhenius, Kjellberg and Libby (o. c.)

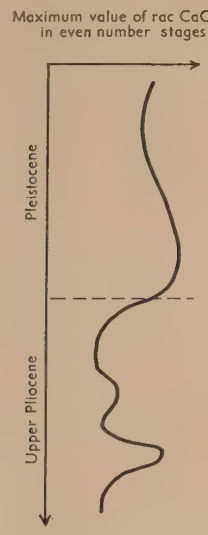

Fig. 1.1.6.2. The graph illustrates schematically the variation with time of the maximum concentration and rate of accumulation of calcium carbonate within the stages. High maximum values occur in Upper Pliocene and the Lower Pleistocene maxima are very high. — The figure has been drawn as to correspond approximately to the subfacies represented by core 58.

especially of the bottom water with which the particles remain in contact for a long time before being definitely buried. Further the rd is influenced by the total rate of deposition. Arctic and Antarctic waters have a high aggressiveness, and the dissolution of calcium carbonate at low latitudes and great depths is ascribed to the inflow of polar bottom and deep water. In the Pacific Ocean[1]) the inflow of Arctic bottom water is negligible in comparison with the supply of Antarctic bottom water. This is due to the fact that the Pacific Ocean is practically closed off from the Arctic Ocean. A climatic change leading to increased growth of the polar ice caps is supposed to increase the aggressiveness of the Pacific Equatorial bottom water comparatively slowly at the beginning (left part of lower graph in fig. 1.1.6.3), as the Antarctic bottom water has to pass vast areas covered by calcareous deposits in the South Pacific and might thus have been partly saturated before reaching the East Eupelagic Equatorial area. In addition, the deep water is supposed to have travelled far and below regions of a high rate of carbonate production and thus to have decreased considerably in aggressiveness before arriving at the area in question here. — The rate of production is believed in the beginning to respond rapidly to the increased rate of

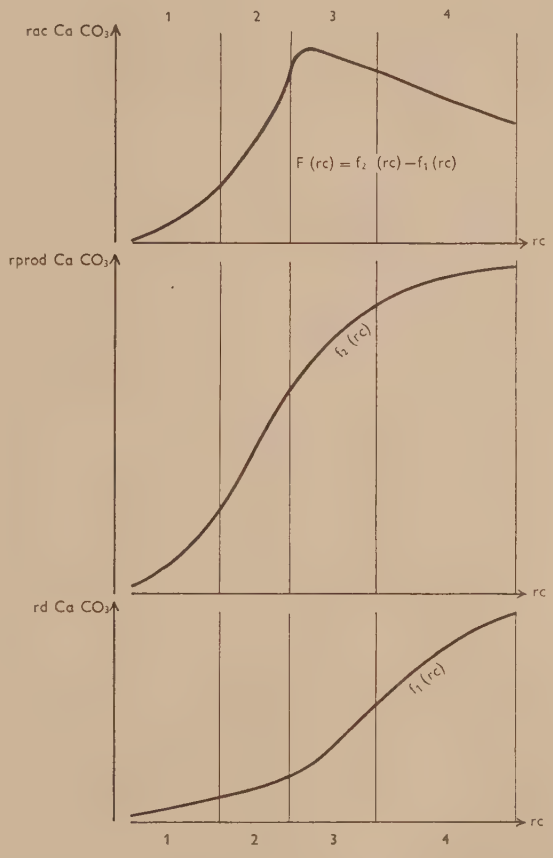

Fig. 1.1.6.3. The inferred rate of oceanic circulation has been indicated on the x-axis and has been divided into four type groups. *Type 1* = Pliocene time units and Pleistocene interglacials with greatly reduced rate of circulation. *Type 2* = Pliocene accumulation maxima and Pleistocene interglacials with an intermediate rate of circulation. *Type 3* = Lower Pleistocene circulation maxima. *Type 4* = Upper Pleistocene circulation maxima (corresponding to the last four Ice Ages). — The ordinates correspond in the lower graph to the inferred rate of dissolution (rd), in the middle graph to the inferred rate of production (rprod), and in the upper diagram to the observed rate of accumulation of calcium carbonate (rac = rprod — rd). The figure is not intended to elucidate quantitatively the functional relationships in question but has been drawn to illustrate qualitatively the suggested explanation of the observed facts.

[1]) The hydrographical data in this paragraph refer to SVERDRUP e. a, o. c.

circulation (middle graph, fig. 1.1.6.3) and as a result the rate of accumulation of $CaCO_3$ (upper graph) can be expected to rise to very high values when the rate of circulation increases from low (type 1 in the graph) to intermediate — low (type 2) and intermediate (3) values. This might explain the comparatively high carbonate peaks (type 2) in Upper Pliocene and the high rates of accumulation of calcium carbonate in Lower Pleistocene.

During the most extensive glaciations in Upper Pleistocene, the North pack ice area extended far out into the Pacific, and great parts of the North Pacific coasts were covered by ice sheets (Flint, o. c.). This development is believed to have contributed markedly to the production of cold, aggressive bottom water. This water, flowing to the south until reaching the Equatorial carbonate compensation line, cannot be expected to have lost much of its undersaturation through dissolving calcium carbonate from the sediment, as since Late Tertiary practically the entire bottom of the North Pacific basin has been covered with carbonate-free deposits. The influx of considerable amounts of this North Pacific Glacial bottom water is therefore supposed to have caused a rapid increase in the rate of dissolution of calcium carbonate in the East Eupelagic Carbonate area (fig. 1.1.6.3, lower graph, rc type 3) and a decrease in the rac $CaCO_3$ (upper graph), which might have become still more marked during maximum glaciation conditions. The diatom distribution (s. f. ch. 1.9) makes it probable that of the nine Pleistocene stages of increased circulation, the last four (8,6,4, and 2) correspond to considerably higher maximum rates of production (circulation) than the preceding ones. Further, of the four last big circulation maxima the one represented by stage 4 appears to have been the highest and the one corresponding to stage 2 the next highest.

The minimum values of the rac $CaCO_3$ attained in the odd-numbered stages appear to be in proportion to the duration of the stage, so that stage 5, which corresponds to the longest age of lowered circulation without subages of increased circulation, displays the most marked general decrease both with regard to concentration and rate of accumulation of $CaCO_3$.

It should be mentioned in this connection that additional confirmation of the correlation between rate of accumulation of calcium carbonate and rate of upwelling of cold deep water in the divergences (rate of surface current circulation) is provided by the percentage distribution of warm- and cool-water elements of the foraminiferal fauna (ch. 1.7). Thus, there is a well-developed inverse relationship between the rate of accumulation of planktonic foraminifera and the percentage of *Globorotalia menardii-tumida*, this species or species group being looked upon as an indicator of warm water (Schott, 1935, Ovey, 1948 Phleger 1951). The Upper Pleistocene strata which have a high rate of accumulation of calcium carbonate and of foraminifera are thus related to cold surface water, but this was probably cooled not only by the spreading of cold surface water from higher latitudes but also by an intensified upwelling of cold deep water.

With regard to the atmospheric circulation conditions during the Ice Ages there are different opinions, some theories assuming a decreased, others an increased rate of circulation and still others a combination of both in sequence. Reviews of these theories are given, e. g. by Flint (o. c.), Willett (1949), and Zeuner (o. c.). The present results are believed to constitute a proof that the Ice Ages were characterized by a strongly increased trade wind intensity. The further geophysical implications of the present interpretation of the East Pacific Eupelagic sedimentary sequence will be treated elsewhere.

There has been a tendency in the literature on marine geology to regard a high Postglacial and a low Glacial concentration of calcium

carbonate as a global rule (s. references in KUENEN, o. c.) and the inverse sequence as indicating slumping or other abnormal conditions. This concept has arisen from the early investigations carried out by the »Valdivia», »Meteor», and other expeditions in the Atlantic Ocean, where the former type of sequence appears to predominate in the areas investigated. As is seen from the present results, the type of sequence is determined by the facies relationships. Thus, in environments where the rate of dissolution increases more rapidly than the rate of production or where this latter rate decreases during the Ice Ages due to deterioration in the conditions of life of the lime-secreting plankton, or to a displacement of the production mechanism, these ages can be expected to correspond to stages with a lowered concentration of calcium carbonate. In the Atlantic Ocean the inflow of polar bottom water plays a bigger rôle than in any other ocean (SVERDRUP, o. c.) and the importance of the dissolution factor as an explanation of the low carbonate content of the deposits from the Last Ice Age has been stressed by MURRAY and PHILIPPI (1908) and by CORRENS (o. c, p. 218).

A study of the Post Glacial climatic evolution in the Hawaiian Islands, based on palynological studies of peat sequences has been carried out by SELLING (1948) and was discussed from a meteorological point of view by WALLÉN (ibid). The general, recurrent evolution of the Hawaiian precipitation climate appears to be in good agreement with the present results, although the equivalency of the substages found by SELLING and in the present work could not be checked as SELLING's work does not include age determinations.

The interpretation of the present results has hitherto been restricted to the East Eupelagic Area. As has been demonstrated in the preceding paragraphs and in part 2, the Equatorial Eupelagic stratigraphy is also found in the East Pacific Ridge sequences no. 39, 42, 45, and 46 (cf fig. 1.1.5), although distorted by local disturbances. In the Central Pacific Archipelagic Area, too, this stratification is well developed, but fades out in the West Pacific, where the Equatorial Current System is not so well defined as in the East Pacific.

During Early and Middle Tertiary and older periods, the atmospheric and oceanic circulation must have differed greatly from present day conditions. No polar ice caps are believed to have existed and the polar production of cold bottom and deep water must have been less than in the Pleistocene. Under such conditions the reduced aggressiveness of the bottom and deep water certainly contributed to the formation of calcareous deposits over great parts of the North Pacific sea floor, which is indicated by the stratigraphy of cores 53, 56, and 57 (cf § 3.3.2 and ch. 2.53, 2.56, and 2.57)[1]). It is interesting to note that the present type of circulation pattern appears to have been established in pre-Pliocene time. This is in agreement with what is previously known about the Tertiary climatic development (CHANEY, 1940, DURHAM 1951, UMBGROVE, 1947).

1.2 Titanium, absolute chronology and rate of accumulation

1.2.1 Previous work.

As has been indicated by RANKAMA and SAHAMA (1950, p. 563) the soluble salts of titanium are readily hydrolyzed and at weathering titanium is entirely concentrated in the resistates and hydrolyzates. In the latter titanium is present as sphene, ilmenite, brookite and probably also as anatase (FREDERICKSON, 1948). According to RANKAMA and SAHAMA (o. c.) much of the titanium contained in sphene passes into solution at weathering but is readily reprecipitated as brookite.

The titanium content of Atlantic sediments

[1]) On the basis of results recently obtained, R. Revelle has suggested a change of depth of the Pacific basin as an additional possible explanation.

was investigated by CORRENS (o. c.) and recalculated on a calciumcarbonate-free basis. CORRENS found values varying between 0.5 and 1 % TiO_2 in most parts of the Equatorial Atlantic with a dominant pelagic type of deposition, and values below 0.5 % in areas where great amounts of wind and water borne resistates are carried out from the continents. Other low values were found in the open South Equatorial Atlantic, where they might be explained by admixture of considerable amounts of biogenous silica. High values (> 1 %) are connected to areas where admixture of basic pyroclastic material or resistates from basic igneous rocks occurs. CORRENS also investigated the grain size distribution of the titanium minerals contained in the sediments and found that the main part of this element was concentrated in the non-colloidal fractions, with a small maximum in the grain size group 5,5 — 1 μ. A statistical treatment of CORRENS' results has been carried out by KOCZY (1950 and 1951).

CLARKE and STEIGER (CLARKE 1924) have analyzed samples of pelagic clays for their content of titanium. These values give the order of magnitude of the element concentration in pelagic hydrolyzates but cannot be used to estimate the content in eupelagic clays as no data are available with regard to the factors of enrichment and dilution (cf. below) in the different localities. The present results indicate that many enriched samples are included, as the average content found by CLARKE and STEIGER is high (0.98 %).

REVELLE (1944) included the analysis of titanium in his study of the samples collected from the Pacific Ocean by the Carnegie and found a very constant amount of appr. 0.8 % TiO_2 in the North Pacific clays. Calcareous and siliceous oozes displayed concentrations in proportion to their content of minerogenous matter. These results confirm REVELLE's general observation that the minerogenous matter deposited in the North Pacific Ocean is uniform with regard to texture as well as to mineralogical and chemical composition. From this REVELLE concluded that the minerogenous matter is mainly of continental origin and has been carried to the place of deposition chiefly suspended in the sea water.

The observations of the uniform composition of the minerogenous matter deposited in the North and Equatorial Pacific forms the basis of KUENEN's lutite veil concept (1950, p. 347). According to KUENEN's hypothesis most of the minerogenous matter deposited under pelagic conditions is derived from a very dilute suspension of fine-grained hydrolyzates mainly originating from the continents and the continental shelves and circulating in the oceans such a long time before being deposited that it has been thoroughly mixed and has attained a uniform and cosmopolitan character. According to KUENEN the average amount of lutite suspended in a water column of average oceanic depth and with a cross section of 1 cm^2 may be appr. 75 mg. Further KUENEN assumes that in the eupelagic environment, as defined in the present work, the amount of matter settling per surface and time unit from the all-oceanic lutite veil is practically constant.

1.2.2 Aims and conditions of the present investigation.

The aim of the present investigation was to study quantitatively the accumulation of lutite in the East Eupelagic area and on the East Pacific Ridge and to check the validity of KUENEN's lutite veil concept. If this hypothesis were found to be correct or if it were found to be approximately valid and the deviations could be measured, determinations of the rate of lutite accumulation would form a valuable basis for establishing an absolute time-scale and for evaluating the rate of accumulation of other components of the deposit. The lutite concentration cannot be measured directly, but CORRENS' investigations of Atlantic sediments and especially REVELLE's

results from the Pacific, quoted above, have shown that in the eupelagic environment titanium is a good indicator of the amount of lutite. Silica cannot be used for this purpose as biogenous silica is added from planktonic and benthonic organisms. Aluminium theoretically offers good possibilities as well as zirconium, but analytical considerations very much favour the use of titanium as a measure of the lutite concentration. The advantages of using titanium have also been stressed by WISEMAN (WISEMAN and OVEY 1950).

1.2.3 Theoretical considerations.

The problem outlined above was approached by investigating the amount of titanium contained in columns of constant cross section area and extending from the present sediment surface down to different stratigraphical levels. One approximation is necessarily involved due to the sampling method used. As is described in § 4.1.5 the individual sample slices are appr. 1.5 cm thick and such slices have been extracted with intervals of mostly 10 cm. As the 8.5 cm column pieces between the samples have not been analyzed, these must, as far as composition is concerned, be regarded as representative of the former. Thus a possible source of error is introduced as very high or very low values might theoretically occur in the column pieces which were not investigated. The probability of low values escaping representation is less than of high values, as the latter are found in strata where the concentration change per unit length of the column is high, due to the low rate of accumulation. This source of error was foreseen when the sampling method was outlined but as it was not known at that time if quantitative agreement would at all be obtained from the comparative titanium investigations and as the exclusion of this uncertainty factor would have involved a doubled amount of samples, the sampling system mentioned above was applied. — Each sample is now regarded as representing a stratum comprising half the overlying untouched column piece, the sample slice, and half the underlying untouched column piece.

The analytical results are originally expressed as mass of TiO_2 per mass unit of salt-free sediment, the corrections for salt content being calculated from the chlorinity values (§ 1.12.1).

The values of mass of titanium per mass unit of sediment have to be recalculated to mass of titanium per unit volume of wet sediment. For this purpose has been used the functional relationship between the salinity (chlorinity) and the water content on one hand and between the water content and the specific gravity on the other, which have been deduced in § 1.12.3. Systematical deviations from these relationships form a theoretical source of error.

The content of titanium in a column with a cross section of 1 cm^2 and extending from the sediment surface down to the level p is in the following designated $\sum_0^p TiO_2$ or simply ΣTiO_2 and is expressed in mg.

1.2.4 Checking of deviations in the lutite accumulation.

A means of checking the changes in the rate of lutite accumulation in space is provided by comparing several cores far apart, which are stratigraphically correlated by means of isochronous levels. Cores 58—62 form a very suitable material for such studies as they record paleohydrographical and paleoecological changes which are believed to culminate simultaneously over the area in question (§ 1.1.3). Core 58 is located at 6° 44′ N and core 62 at 3° S. The latitudinal size of the test area is thus 9° 44′ or 1 080 km.

The method of testing the deviations in accumulation of titanium is exemplified by fig. 1.2.4, showing the Late Pleistocene variations in carbonate content of cores 59 and 60. Core 60 has been selected as the standard of comparison. Stratigraphical levels, which are

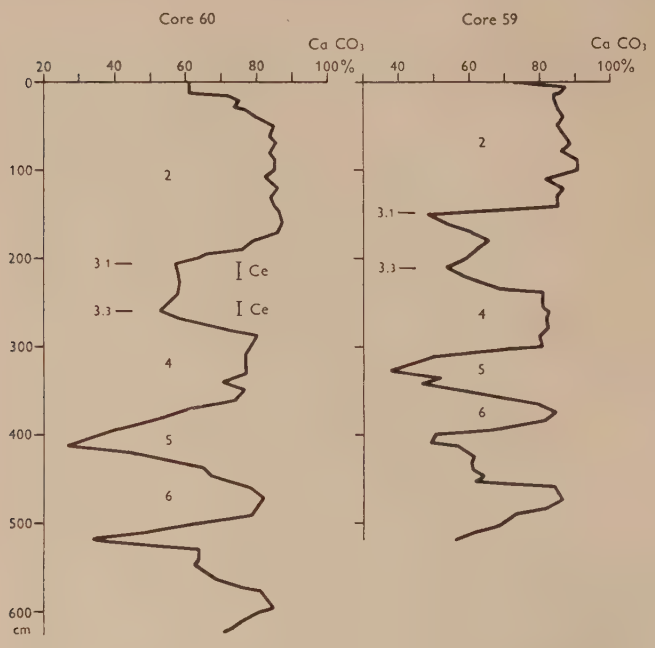

Fig. 1.2.4. Vertical distribution of calcium carbonate in the eupelagic cores 59 and 60. The graph is intended to illustrate the method of checking regional deviations in the rate of accumulation of titanium. The members 3.1 and 3.3 are assumed to be equivalent in both cores. The measures *Ce* (thicknesses of the central strata of the members 3.1 and 3.3) correspond to the estimated uncertainty of the stratigraphical correlation. The levels 3.1 and 3.3, indicated by horizontal strokes in the diagrams, indicate the most probable location of the stratigraphical centers of the central strata.

believed to be equivalent and isochronous are identically labelled in the two diagrams (cf § 1.1.5 and ch. 3.3). Thus equivalency is assumed between e. g. the minimum of substage 3.3 in core 59 and the corresponding minimum in core 60 (fig. 1.2.4). As the course of the calcium carbonate curve might be slightly modified by variations in the amount of biogenous silica and as the curve is interpolated between the levels investigated, a certain error influences the accuracy of the stratigraphical correlation. The source of error caused by the varying amount of biogenous silica can be excluded by using the curve of rate of accumulation of calcium carbonate for the detail correlation instead of the calcium carbonate concentration curve under the assumption that the rate of lutite accumulation was not subject to great and rapid changes. The remaining correlation error is designated the stratigraphical uncertainty.

Assume that the level 3.3 in core 59 (fig. 1.2.4) is given. As the most probable isochronous level in core 60 is regarded the one likewise labelled 3.3. Due to the stratigraphical uncertainty involved, this level could possibly be located higher or lower in the column. The distribution of properties in this core, however, make it improbable that the level 3.3 is located outside the stratum Ce 3.3, indicated in the graph. Ce is here called the central stratum of substage 3.3 and the level 3.3 is called the center of the central stratum.

Assume further that the sources of error, indicated in the preceding paragraph and earlier in this, did not exist, and that the amount of titanium accumulated per unit surface of core 59 and 60 since the minimum of subage 3.3 were exactly identical. Under such conditions $\sum_{0}^{3.3} TiO_2$ would be equal in both cores. In reality deviations occur. These are expressed as the difference $\Sigma\, TiO_2$ (core 60) $- \Sigma\, TiO_2$ (core 59) $= d$. Assume that the deviation has been determined e. g. of $\sum_{0}^{3.1} TiO_2$ and has been found to be d_1 and further that a new discrepancy d_2 enters when the summation is extended to the level 3.3 ($d = d_2$ for $\sum_{3.1}^{3.3} TiO_2$). In such a case the deviation of $\sum_{0}^{3.3} TiO_2$ will be $= d_1 + d_2$. In order to investigate the new discrepancies which enter when the summation is extended from one stratigraphical level to the subsequent one, the stepwise change in the value of d has been calculated $= \Delta d = d_n - d_{n-1}$. The $\Sigma\, TiO_2$ of the central stratum is designated d_0 and is a measure of the possible error

TABLE 1.2.5

Stage or substage no.	$\Delta d/d_0$				d_0 mg TiO_2
	core 58	core 59	core 61	core 62	core 60
2	—0.69				16
2.2		—1.33	—0.67	+0.44	9
3	—0.96				27
3.1		+0.21	+0.07	—0.57	14
3.2		+0.63		+0.25	8
3.3		—1.18	—0.18	—1.82	11
4	+1.30				23
4.2		0.00	—1.33	+0.17	6
4.4		+0.22	+0.09	+1.27	11
5	+2.00	+1.56	0.00	+1.00	9
6	+1.20	+3.00		+4.40 (+0.40)	5
7	—3.90	+0.09		+1.18 (—0.64)	11
8	+1.04				28
8.2		—0.29		—0.29	14
8.4		+0.56		—0.41	27
8.6		—1.44		+1.22	9
9	—0.33	—0.56		+0.33	9
10	—0.14	—0.47		+0.19	21
11	—0.69	+0.62		—0.62	13
12	—0.45				15
12.2		—2.00		—1.20	5
12.4		—0.50		+0.25	8
13	—3.66	—0.33		—1.00	6
14	+1.50				10
14.2		+2.83			6
m	1.37	0.90	0.38	0.92 (0.67)	
a	70 cm.	325 cm.	650 cm.	243 cm.	408 cm.

introduced by the uncertainty of the stratigraphical correlation. If Δd is of the same order of magnitude as d_0 the discrepancies in ΣTiO_2 can be explained as entirely caused by the stratigraphical correlation error. If, on the other hand, Δd is considerably greater than d_0 it might be assumed that the other sources of error previously mentioned influence the results, that the titanium content of the lutite has varied, or that the rate of lutite accumulation was subject to local variations.

1.2.5 Results.

The details of the process of calculation of the results are shown in the tables 2.58.13—2.62.13. From these the values of the ratio $\Delta d/d_0$ have been extracted and rearranged in table 1.2.5. The average (m) of $\Delta d/d_0$ is indicated in the bottom of the table. From the table is seen that the greatest deviation is found in core 62, stage 6, where $\Delta d/d_0$, estimated without bias of the resulting discrepancy, amounts to 4.40. As is indicated in § 2.62.13 there is no stratigraphical objection to a correlation which reduces the disagreement to 0.40 which simultaneously lowers $\Delta d/d_0$ in stage 7 from 1.18 to — 0.64. As, however, the greater error corresponds to the first and unbiased correlation, it has been taken into account and is an example of the stratigraphical uncertainty. The reason for the high relative error in this case is not so much a high value of Δd as a low value of d_0 (5 mg TiO_2/cm^2). This might also be the cause of the high value of $\Delta d/d_0$ in the same stage of core 59 (3.00). Except for these two values only five values out of forty-

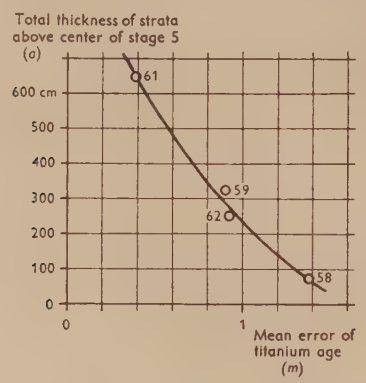

Fig. 1.2.5. Relation between the average thickness of the correlated strata and the average relative deviation of the titanium age determination. Core numbers are indicated in the graph. At the determination of the relative deviation one degree of freedom (core 60) is lost.

one exceed $\Delta d/d_0 = 1.50$ in the core group 59—62. The agreement in this group is looked upon as very good with regard to the methodical sources of error involved.

In core 58, the average Middle and Upper Pleistocene total rate of accumulation (a) is only 0.35 cm/1 000 years and the entire Pleistocene is compressed to a series, slightly thicker than four meters. These conditions make it difficult to recognize substages and the error in $\Sigma\ TiO_2$, caused by a very small error in the stratigraphical correlation, is high. As a result two great values of $\Delta d/d_0$ occur, viz. in the stages 7 and 13. It is symptomatical that these great deviations are connected to carbonate-minimum stages, where the titanium content is high and where the possibilities of error in $\Sigma\ TiO_2$ are increased. In spite of these two deviations and of the unfavourable conditions the average error is astonishingly low ($\Delta d/d_0 = 1.37$) and the agreement in $\Sigma\ TiO_2$ is regarded as good.

As is seen from table 1.2.5, the sign of the ratio $\Delta d/d_0$ changes frequently within the sequences investigated. This demonstrates that there is no permanent local deviation in the rate of lutite accumulation. — At the bottom of table 1.2.5 is indicated the average (m) of $\Delta d/d_0$ within the cores, and the total thickness (a) of the strata above the minimum of stage 5. This level was chosen as a lower limit of the thickness measure a as it is the lowest one recognized in core 61 without the aid of the extrapolated titanium age. Fig. 1.2.5 demonstrates graphically the correlation between m and a. From this graph is seen that there appears to be an inverse relationship between a and m. As indicated above, a qualitative relationship of this kind could be expected as both the analytical error and the stratigraphical uncertainty decrease and the representativity of the samples increases where the rate of biogenous accumulation is high, the time-rock units are thick and easy to subdivide, and the change in titanium concentration per unit change of depth is small. The quantitative relationship between a and m, although represented by only four points, is, however, astonishingly good. This indicates that the deviations found in the $\Sigma\ TiO_2$ to a large extent arise from methodical errors, as the deviations shown in table 1.2.5 do not appear to be systematical.

The results of the comparative investigations of the accumulation of titanium thus are subject to only relatively small deviations and these can be assumed only in a minor degree to arise from deviations in the proportionality of lutite and titanium concentrations or from local discrepancies in the rate of lutite accumulation. The conclusion is that the rate of lutite accumulation has been constant with regard to space all over the East Eupelagic area within the limits of the analytical error.

1.2.6 Time-density relationships of the lutite veil.

The present results do not give any direct information whether there have been any changes of the rate of lutite accumulation with time and the author has not found it possible to check quantitatively such changes. It should, however, be stressed that local changes with time of the rate of lutite accumulation greater than the experimental error, are exclu-

ed by the present results. The possibility still existing is that the density of the all-oceanic lutite veil has changed during the Pleistocene. As reasons for an increased density of the lutite veil during the Ice Ages might be suggested a rejuvenated erosion of shelf sediments caused by the glacially controlled lowering of the surface of the ocean, the increased supply of glacifluvial lutite to the sea and the increased periglacial eolian transport possibly resulting in an increased net transport of eolian lutite to the sea. Tectonic and volcanic events are believed to play a regionally limited role.

On the other hand it may be assumed that the amount of lutite escaping from coagulation in the shelf and hemipelagic environments is, within the limits of Pleistocene conditions, practically constant.

Although there appear to be no means available at present to control quantitatively the changes in the density of the lutite veil with time, there is reason to assume that these changes were small and possibly negligible. The evidence for this is given in § 1.5.2. Thus constancy of the rate of lutite accumulation with regard to space can be regarded as proved and with regard to time as a probable assumption as far as the East Eupelagic Pleistocene sequences are concerned.

1.2.7 Obstacles for regional extrapolation.

The present results should not be taken as a reason to assume constancy in the rate of minerogenous accumulation in other areas without checking this assumption, as several disturbing factors may occur, which cannot be excluded except by comparison of the lateral changes in the thickness and composition of the strata. Deviations in the rate of lutite deposition appear to be common on topographical rises and in depressions, and are believed to be due to the activity of currents. The decreased rate of lutite deposition on the Mid-Atlantic Ridge has been demonstrated by CORRENS (o. c., p. 197—198). The sequence of correlatable cores from the East Pacific Ridge (ch. 2.39, 2.42, 2.45, 2.46) indicate that also in this area considerable local deviations occur in the rate of lutite accumulation (cf ch.3.3 § 2.39.13 and fig. 1.1.5, left section).

Even if it is not possible to extrapolate without proof the results from the East Eupelagic area in the Pacific Ocean to other regions, it can be assumed that the high degree of spatial constancy and the probability of time constancy might be found in other areas with a favourable bottom topography and freedom from continental and archipelagic influence.

1.2.8 The titanium content as an indicator of absolute age.

If spatial constancy of the rate of titanium accumulation has been proved within an area and if time constancy of this rate can be demonstrated to be probable, it is clear that there is reason to assume that the $\sum_{0}^{n} TiO_2$ is in direct proportion to the age of the level n. In the eupelagic environment the titanium content of a sediment column with a constant cross section is thus an expression of the age of the lower boundary of the column. *A priori* the factor for conversion of titanium content to calendary units is not known. In order to elucidate this relationship core 61 B (45 cm), including the present sediment surface, was subjected to determination of the radiocarbon content (ARRHENIUS, KJELLBERG, and LIBBY, 1951) and the age of the lower boundary was calculated by integration of the radiocarbon decay function. The lower boundary of core 61 B was found to have an age of 14 200 $\pm$ 900 years and the corresponding Σ TiO_2 to be 7.59 mg TiO_2/cm^2. 10 000 years thus correspond to 5.35 $\pm$ 0.35 mg TiO_2/cm^2. This value has been used for calculating the ages indicated in pl. 2.58—2.62. The error in the titanium age caused by the standard deviation of the radiocarbon age amounts to $\pm$ 6.3 % and the

average error inherent in the Σ TiO_2 is estimated to appr. $\pm$ 3 % of the true age (cf. § 1.2.5 and ch. 2.58—2.62). These standard deviations, although fairly small, can certainly be decreased by a refinement of the analytical methods.

1.2.9 Calculation of rate of accumulation.

If P is the mass of an element in a eupelagic sediment sample, and TiO_2 is the corresponding mass of titanium oxide, the ratio P : $TiO_2 = r$ expresses the number of mass units of P per mass unit of TiO_2. But as the mass of TiO_2 found in a column of unit cross section area is in the eupelagic environment by definition (§ 1.0.2) directly proportional to the time elapsed during the accumulation of the column, the ratio r expresses the mass of P accumulated per unit time i. e. the rate of accumulation of P (rac P). If 0.535 mg is chosen as the mass unit of TiO_2, one unit of TiO_2 per cm^2 corresponds to 1 000 years. If also the mass of P is given in mg, the rate of accumulation will be expressed in mg of P per cm^2 and 1 000 years. For practical reasons the unit 1 mg/cm^2 · 1 000 years has been named 1 fòr (from Greek $\varphi o \varrho \acute{\alpha}$, intensity). From this unit is derived the unit 1 cfor = 0.01 for and 1 kfor = 1 000 fors. The rate of accumulation has been calculated for calcium carbonate, humus carbon, nitrogen, phosphorus, and biogenous silica, and has been drawn as a function of depth in pl. 2.58—2.62. The rac $CaCO_3$ as a function of time is shown in fig. 1.1.6.1. The rac of radiolaria, foraminifera, and diatoms has been expressed as number of specimens per cm^2 in 1 000 years.

The total rate of accumulation is in inverse proportion to the concentration of titanium. Thus

$$\text{rac tot.} = \frac{53\,500}{TiO_2 \cdot 10^5} \qquad (1.2.9.1)$$

where rac tot. is expressed in fors, and

$$\text{rac tot.} = \frac{53\,500}{q \cdot TiO_2 \cdot 10^5} \qquad (1.2.9.2)$$

where rac tot. is expressed in cm of wet sediment per 1 000 years and q is the number of milligrams of dry, salt-free sediment per ml of wet sediment (cf ch. 1.12).

1.2.10 Titanium content of the eupelagic lutite.

The titanium content of the eupelagic lutite cannot be directly measured, as a pure deposition of lutite has not been found and cannot be expected in the eupelagic environment. Besides, in deposits with a high content of lutite and thus with a low rate of accumulation, the formation of authigenic manganese and iron ore minerals is favoured, which complicates the investigation. For the estimation of the ratio lutite: titanium, eupelagic carbonate sediments therefore offer the best material. These sediments consist of the three main components; calcium carbonate, biogenous silica and lutite. Accessory components are believed not to exceed 1 % and are negligible in this connection. The biogenous silica is present in the form of skeletal remains of siliceous organisms and as colloidal silica (coll. si_b) derived through peptization of such remains. No possibility has been found to measure directly the amount of colloidal biogenous silica. The concentration of silica present as recognizable skeletal remains has been estimated by counting the number of radiolaria $> 150\,\mu$ per gram sediment (R) and assuming that this number is directly proportional to the mass concentration in question. Thus

$$CaCO_3 + k \cdot TiO_2 + m \cdot R + \text{coll. } si_b = 1 \qquad (1.2.10.1)$$

This equation was applied to 606 sets of values of $CaCO_3$, TiO_2 and R from the East Eupelagic carbonate area and the best values of k, m, and coll. si_b were calculated by the method of least squares (Arrhenius and Blomqvist vol. 5, pt 5). A discussion of the sources of error, the deviations, and the multiple correlation is found in the work cited above. The best values found were k = 136, m = $38 \cdot 10^{-7}$ and coll. $si_b = 0.11$.

If a pure lutite is assumed, i. e. if all factors of the left member of the equation (1.2.10.1), except $k \cdot TiO_2$ are put $= 0{,}136\ TiO_2 = 1$ and $TiO_2 = 0.00733$. This is the most probable value of the concentration of titanium in pure eupelagic lutite in equilibrium with air of 60 % moisture at 20° C.

The determination of this constant enables the estimation of the rate of accumulation of lutite in the eupelagic environment which is simultaneously the theoretical minimum eupelagic total rate of accumulation. Insertion of the value for k in the equation (1.2.9.1) gives

$$\text{rac tot.} = \frac{53\,500}{733} = 73 \text{ fors} \quad (1.2.10.2)$$

The highest titanium value found in the material investigated is $TiO_2 = 0.00650$ (core 57, 250 cm) which gives a total rac of 82 fors if eupelagic conditions are assumed. The value of q in this sample is 287 mg/ml. Insertion in equation (1.2.9.2) demonstrates that the rac value 82 fors corresponds to 0.29 cm/1 000 years in this case.

The lowest concentration of titanium met with in the East Eupelagic area is $TiO_2 = 0.00006$ (core 62, 460 cm), corresponding to a total rac of 8.9 kfor. q is here = 1117 mg/ml and the maximum total rac found thus corresponds to 8.0 cm/1 000 years (wet sediment).

1.3 Biogenous silica

The amount of biogenous silica in the eupelagic sediments of the East Pacific was calculated as the remainder after subtracting the calcium carbonate and the lutite component. The amount of lutite was calculated from the concentration of titanium, using the relationship $L = 136 \cdot TiO_2$, where L and TiO_2 are the concentrations of lutite and TiO_2 respectively (ARRHENIUS and BLOMQUIST, o. c.). Thus $si_b = 1 - (L + CaCO_3)$, if si_b is the calculated concentration of biogenous silica. This method of calculating the concentration of biogenous silica is applicable only in the eupelagic environment. In very slowly deposited eupelagic sediments, considerable amounts of halmyrogenous oxidates and precipitates (§ 1.12.6) cause too high values of si_b The equation given above has in such cases to be written: $si_b = 1 - (L + CaCO_3 + M)$, where M is the concentration of halmyrogenous oxidates and precipitates (mainly iron, phosphorus and manganese compounds). In the present case the calculation of si_b has been restricted to the calcareous eupelagic sediments, where M is negligible.

The calculated concentrations of biogenous silica are shown in pl. 2.58—2.62, col. Biogenous silica, and the calculated rate of accumulation of biogenous silica in pl. 2.59—2.62, col. Biogenous silica, dashed curve (scale at the lower ends of the columns). A synoptical survey of the distribution of the rac of biogenous silica is given in fig. 1.3. From this it is seen that regionally, the highest rac is found in core 61, which is located below the Equatorial Divergence. The maximum rate recorded in the East Eupelagic area is found in the circulation maximum substage 4.2 and amounts to 860 fors. The concentration of si_b is increased in the odd number stages(circulation minima). This is due to the decreased dilution with calcium carbonate, and the rac of si_b is markedly decreased in most odd number stages and substages. The most marked decreases in the rac of biogenous silica occurred during ages 3 and 5, assumedly corresponding to the Last and Penultimate Interglacial Ages. The Pleistocene strata of core 58 record a low average rac of si_b and the minimum values, attained in the odd number stages (low rate of circulation) are only a few fors. The Pliocene conditions are uniform in comparison with the Pleistocene, both in cores 58 and 62. The extensive decrease of the average rac si_b in the Pleistocene of core 58 might be caused by an increased rate of dissolution of biogenous silica or by a decreased rate of production of

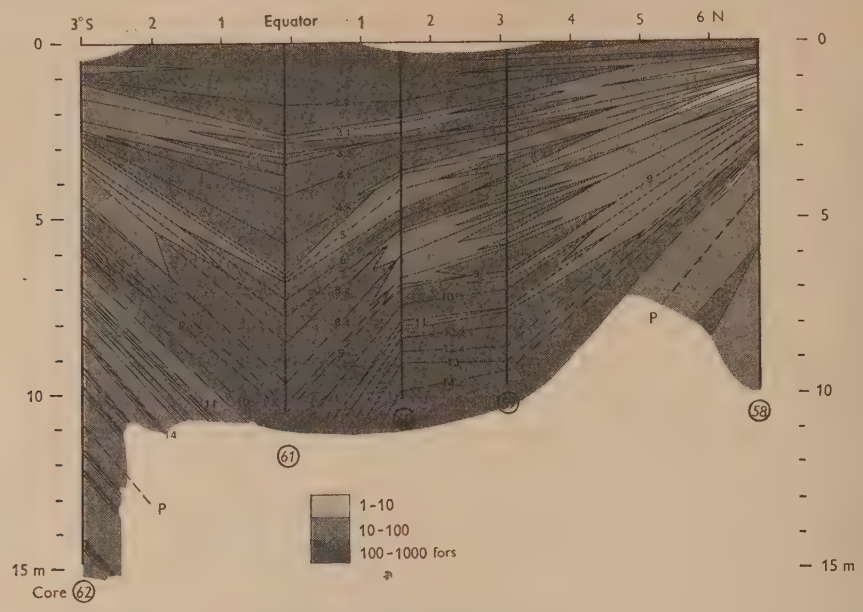

Fig. 1.3. Rate of accumulation of biogenous silica in the East Eupelagic carbonate area. Vertical lines correspond to sediment cores. Core numbers are indicated below the diagram. The stratigraphical position of stage and substage maxima and minima are indicated by labelled lines. P = Pliocene — Pleistocene boundary.

biogenous silica. It is not known which of these alternatives is the correct one. Microscopical analyses of the Pleistocene strata of core 58 (ch. 2.58) show that many siliceous organisms are extensively corroded and the results gained (Arrhenius and Blomquist, o.c.) make it probable that a great part of the biogenous silica is present in colloidal form. It is possible that the peptization of the siliceous structures had proceeded a long way before burial of these, and that parts of the silica gel thus escaped from the sediment. If this is true, the main factor responsible for the increased rate of dissolution of biogenous silica in the Pleistocene odd number stages is believed to be the decreased total rate of accumulation during the corresponding ages, leaving the siliceous fossils in contact with the bottom water for a long time before burial.

Petrographical dominance of biogenous silica occurs only in a thin stratum of stage 5 in core 59 (44 % si_b, 37 % $CaCO_3$, 19 % lutite). Siliceous ooze is thus of no quantitative importance in the East Eupelagic area.

1.4 Organic matter (marine humus)

1.4.1 Previous work. Apparent disagreements and agreements.

The organic matter of recent marine sediments has attracted great interest, above all (Sverdrup, e. a., o. c.) as it is considered to have been the source of petroleum. Investigations of the content of organic matter of pelagic deposits have been published by Correns (1937) Trask (1939), Revelle (1944), Waksman (1933), Wiseman and Bennett (1940) a. o. Surveys of the literature in this field as well as of the results hitherto gained are given e. g. in Sverdrup, e. a, o. c., p. 1008—1016, Trask (1939, p. 428—453) and Kuenen (1950, p. 399—403). As an indicator of the total content of organic matter has been used the content of carbon (e. g. by Correns), nitrogen (e. g. by Revelle,) or both (Trask (partly)), Waksman, Wiseman and Bennett). In those cases where only one of these elements was investigated, a linear relationship has been assumed between carbon and nitrogen concentrations so that the total

content of organic matter could be calculated either from the carbon or the nitrogen content. Deviations in the quotient C/N were soon revealed but were believed to be due to normal statistical dispersion. WISEMAN and BENNETT (o. c.), whose work is the first systematic investigation of the carbon-nitrogen relationship in pelagic sediments, pointed out, however, that great and apparently irregular variations occur in the ratio C/N and that nitrogen is therefore no adequate measure of the organic matter. The present author (1950) demonstrated that there is in subaquatic sediments a regular increase of the ratio C/N with decreasing content of organic matter. The relationship found was confirmed by analyses compiled from several authors. WISEMAN and BENNETT's samples, however, differed greatly from this relationship and were found to be abnormally rich in carbon. According to a suggestion by the present author at that time the excess of carbon in WISEMAN and BENNETT's samples from the Arabian Sea might be explained by assuming a systematic analytical error caused by carbon dioxide from undecomposed dolomite. The present results, however, clearly demonstrate that all calcareous pelagic sediments from the East Pacific are characterized by an abnormally high and greatly varying ratio C/N and that WISEMAN and BENNETT's results are in good agreement with the distribution of carbon and nitrogen in Pacific calcareous oozes. The normal logarithmic relationship between C and N on the other hand holds true in pelagic clays. These conditions will be further treated below.

1.4.2 Regional distribution.

The frequency distribution of the logarithm of the carbon and nitrogen content is shown as a function of the geographical latitude in fig. 1.4.2.1 and 1.4.2.2. The highest average and extreme values both of carbon and of nitrogen are found in the Galapagos area, especially in core 39. In the East Pacific Ridge sediments north of the Galapagos area, the average content of organic matter, as reflected by the carbon concentration, decreases regularly to the north. This is believed to depend mainly on the latitudinal change of organic production in the surface of the sea within this region. The comparatively high rate of minerogenous accumulation might contribute to the preservation of the organic matter and thus to the high average content in the East Pacific Ridge section as compared with the East Eupelagic section. In the former section nitrogen is not as regularly distributed as carbon. Comparatively high contents are frequent, not only in the Galapagos area, but also in cores 42, 45, and 46. The stratigraphy of these cores (ch. 2.42, 2.45 and 2.46) indicates that redeposition of locally abraded material is of subordinate importance whereas redeposition appears strongly to influence the neighbouring cores 41, 43, 44, and 47. It is believed that the redeposited material, originally belonging to another cycle of deposition, is comparatively poor in nitrogen and that the assumed high content of redeposited matter in cores 41, 43, 44 and 47 is the reason for the low average nitrogen content in these. The carbon content also appears to be affected by the redeposition but not as extensively as the nitrogen (s. f. § 1. 4. 4). The nitrogen content of the North Equatorial clay cores is high, both in the East Pacific Ridge section and in the East Eupelagic section (cores 48, 50, 51, 54, 55 and upper 57). This is in good agreement with the distribution found by REVELLE (o. c.). The very low average nitrogen content found in core 53 is typical for the calcareous Tertiary sediments which constitute this core. The abnormally low values forming the left part of the distribution in core 57 are likewise connected to the calcareous Tertiary sediments which form its basal strata. The corresponding low values in core 56 are derived from the basal calcareous Tertiary stratum and from the directly overlying clay.

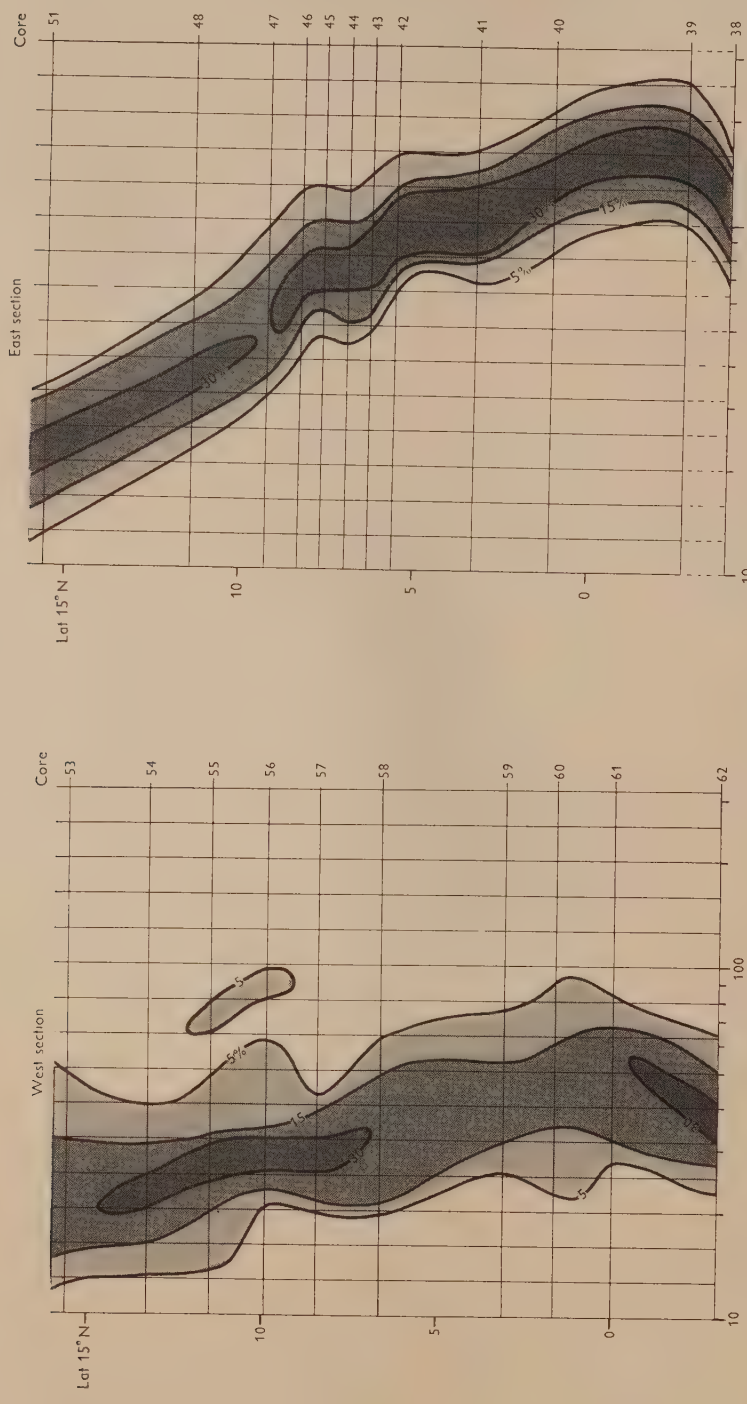

Fig. 1.4.2.1. Frequency distribution of carbon as a function of latitude in the East (right diagram) and West (left diagram) sections through the East Equatorial Pacific sediments (cf. fig. 1.0 at the end of this part). For the construction of the diagram, s. § 1.0.3.

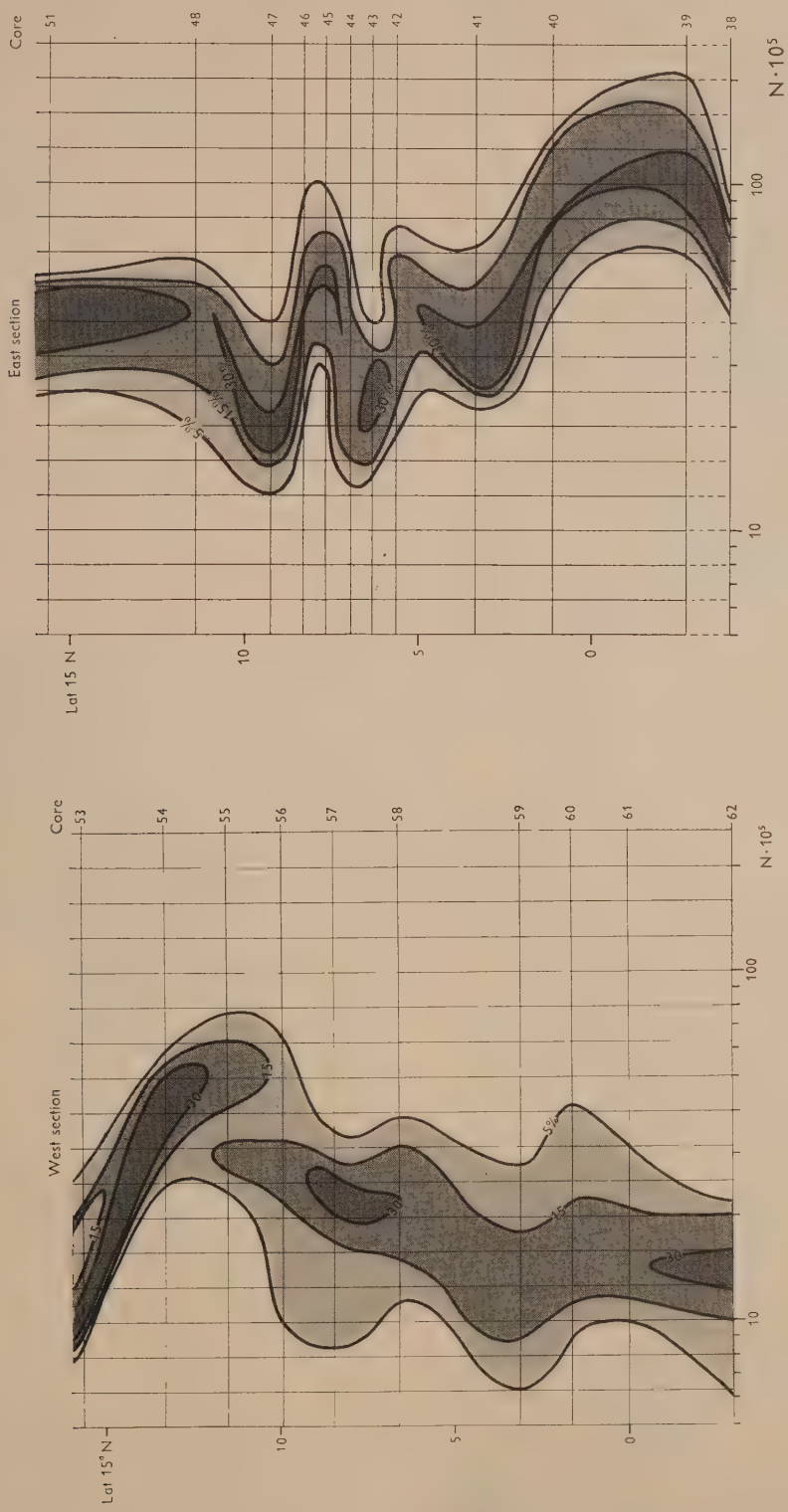

Fig. 1.4.2.2. Frequency distribution of nitrogen as a function of latitude in the East (right diagram) and West (left diagram) sections through the East Equatorial Pacific sediments.

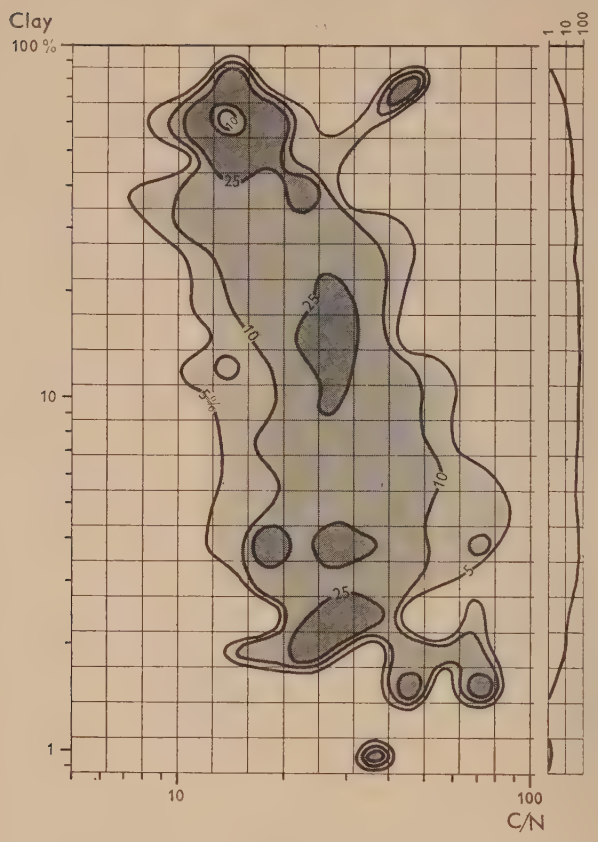

Fig. 1.4.3.1. The ratio C/N as a function of the concentration of clay in the East Eupelagic sediments. Clays, marl oozes, and marly chalk oozes have a markedly decreased ratio C/N. That this is due to an increased content of nitrogen is seen from fig. 1.4.3.2 and 1.4.3.3 (For construction of the isoplethic diagram, see § 1.0.3).

From the calcium carbonate compensation line (at core 57) there is a slight general increase in the average carbon content towards the equator, whereas the average nitrogen content decreases. This is believed to be a manifestation of the inverse relationship between the ratio C/N and the clay content of the deposit (cf. § 1.4.3).

1.4.3 The carbon-nitrogen relationship.

As has been stressed by the previous authors referred to above, neither with regard to quantity nor to composition does the marine humus account for the newly deposited organic matter. Owing to decomposition the rate of accumulation must be assumed to differ markedly from the rate of deposition and the results of Wiseman and Bennett's investigation demonstrate that the decomposition might take place along quite different lines within the pelagic environment. This is confirmed by the present results, which indicate that the most important factor in determining the final carbon-nitrogen ratio is the composition of the sediment. In fig. 1.4.3.1 is shown the logarithmic relationship between the concentration of lutite (ch 1.2) and the ratio C/N. From this figure it is seen that there is a marked increase in the relative abundance of nitrogen with increasing clay content. This fact could be seen already from the regional distribution of carbon and nitrogen (§ 1.4.2)

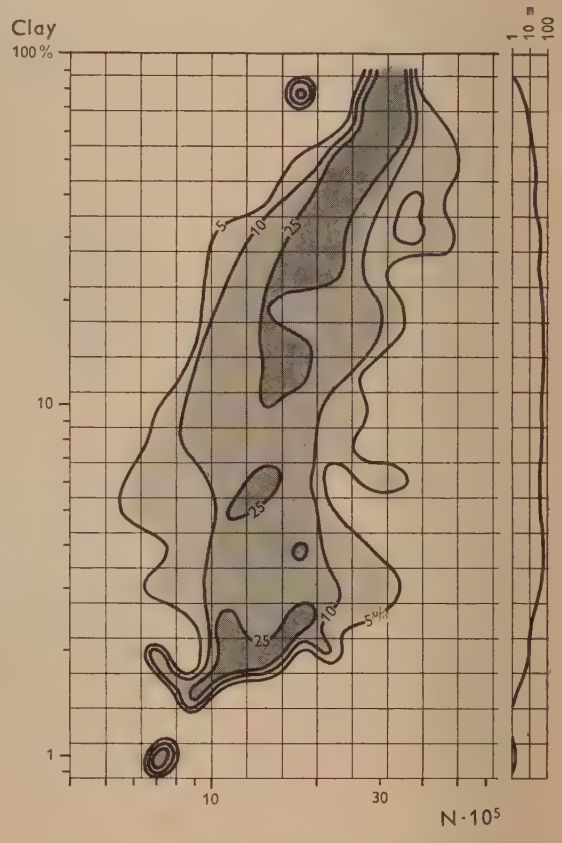

Fig. 1.4.3.2. Nitrogen content as a function of the concentration of lutite in the East Eupelagic sediments. The curvation and slope of the distribution indicate that the nitrogen concentration starts from a value greater than zero in pure chalk oozes, that the content of nitrogen increases with increasing clay content and that the rate of increase decreases with a rising concentration of clay.

and is demonstrated graphically in fig. 1.4.3.2 and 1.4.3.3. From these distributions it is evident that the clayey sediments, in spite of their relative richness in nitrogen, are poor in carbon and thus in organic matter, as nitrogen forms only a subordinate part of this. The high content of nitrogen in Pacific clays was observed by REVELLE, who was, however, misled by the current assumption of direct proportionality between carbon and nitrogen and thus concluded that the clays were relatively rich in organic matter.

The relative abundance of nitrogen in clayey deposits may theoretically be caused by some mass property, e. g. the lack of calcium carbonate, by some property of the clay favouring the conservation of nitrogen, by the low total rate of deposition, by the low rate of deposition of organic matter or by differences in the benthonic faunas and floras decomposing the organic matter in calcium carbonate and clay environments. One possibility, belonging to the second alternative, is that nitrogen during normal marine decomposition is transformed to ammonium compounds and that the ammonium ions are adsorbed to the clay particles but tend to migrate from sediments poor in clay. To test this hypothesis the amount of ammonium nitrogen was determined in core 54 which is very rich in nitrogen and in a stratum of core 40 where postdepositional migration might be suspected. In no case, however, was the relative amount of ammonium nitrogen found to be significant and this hypothesis may therefore be discarded. The present author has not found it possible to judge definitely which of the remaining alternatives is the most probable one, although the discussion below on fig. 1.4.3.4, shows that the rate of accumulation might be of importance.

Fig. 1.4.3.4 shows the carbon-nitrogen relationship in all East Pacific samples. It is evident that the material is statistically heterogenous, one population being distributed

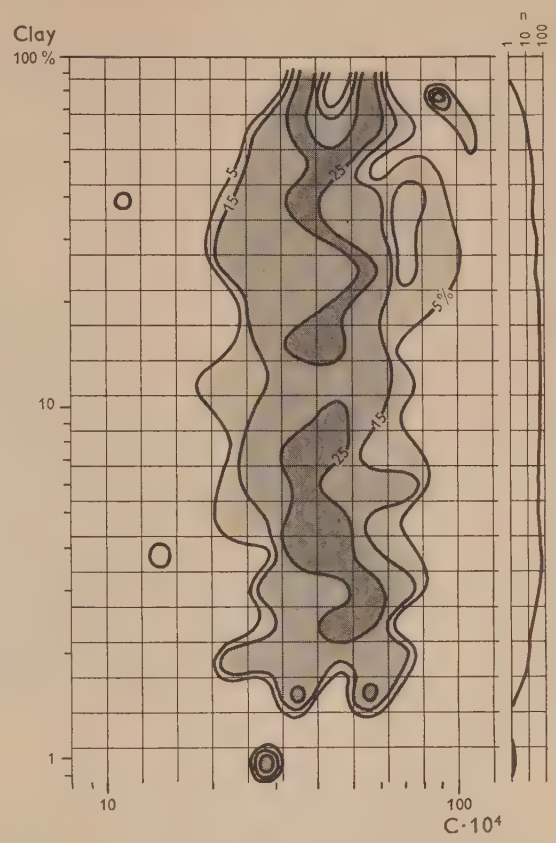

Fig. 1.4.3.3. The relationship between content of humus carbon and of lutite in the East Eupelagic sediments. The average concentration of carbon is practically constant statistically and $\approx 44 \cdot 10^{-4}$, or possibly slightly decreasing with increasing content of clay. As a result the rate of accumulation of carbon is directly proportional to the total rate of accumulation, the changes of which are entirely determined by the rate of accumulation of biogenous matter in the eupelagic environment.

around the equation A (dashed line), the other fairly well agreeing with the equation B (dotted line). Group A represents those strata which have a high rate of accumulation and thus mostly a high content of calcium carbonate. The richest samples are those from core 39. (Samples from the Gulf of Panama, which are rich in detritogenous organic matter have been included for the sake of comparison and are indicated by points above the distribution body). The equation A indicates a slightly increased relative nitrogen content with increasing content of carbon. ($C/N \approx 26$ if $C = 13 \cdot 10^{-4}$ and $C/N \approx 15$ if $C = 316 \cdot 10^{-4}$).

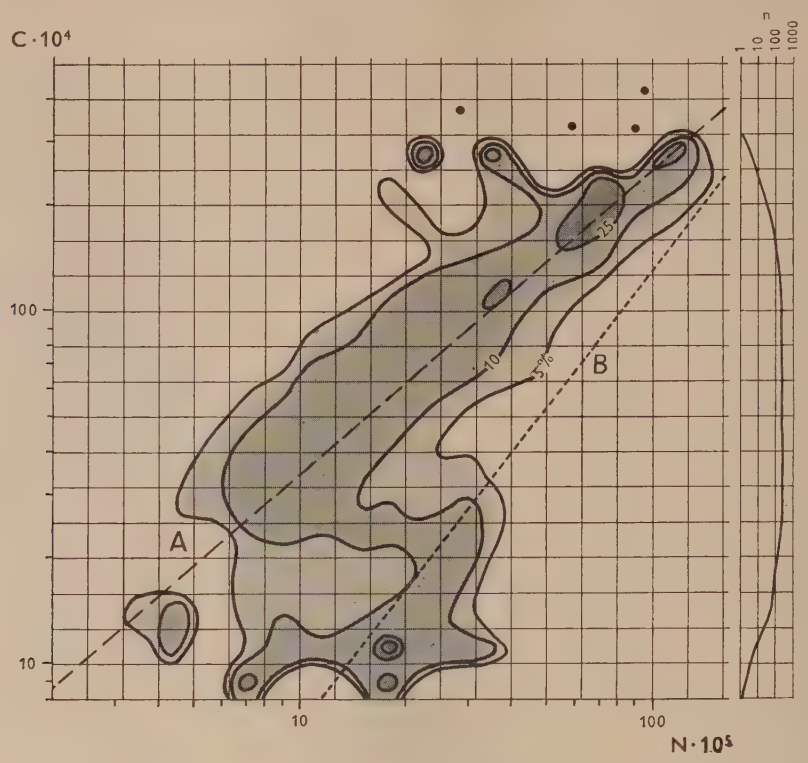

Fig. 1.4.3.4. The carbon-nitrogen relationship in East Equatorial Pacific sediments. Samples with a high total rate of accumulation distribute themselves around the subjectively estimated average equation line A. Pelagic clays form the main part of the body around the line B which corresponds to the equation derived by the present author (1950). The field between the lines A and B is occupied by siliceous and calcareous clays. The isolated group of low carbon and nitrogen values consists of Tertiary marl and chalk ooze from cores 53 and 57.

The isolated group with very low concentrations of carbon and nitrogen is constituted by calcareous Tertiary samples.

The equation B is the one found by the present author (o. c.) to be valid for lacustrine deposits and shelf sediments. The group distributed around this line consists of the pelagic clays from the North Equatorial clay facies (cf. fig. 1.0). Samples from surface strata are those which are richest in organic matter within this group. The ridge connecting group B with group A is formed by samples from the North Equatorial silica facies (fig. 1.0). The samples, low in carbon, which are intermediate between A and B belong to carbonate-poor strata in the Eupelagic Equatorial carbonate facies. These conditions are further illustrated in fig. 1.4.3.5 and 1.4.3.6, where the eupelagic calcareous samples and pelagic clay samples are separately shown.

The location in group A of those sediments from the Galapagos area which have a high rate of accumulation (rac) of organic matter and a high total rac but not a very high content of calcium carbonate as well as the transition from group B to group A of the siliceous clays, which are free from carbonates but have a higher rac of organic matter and total rac than the ordinary pelagic clays, make it probable that the rate of accumulation is an important factor influencing the composition of the organic matter. It is not known, however, whether the total rac or the rac of organic matter exerts this influence.

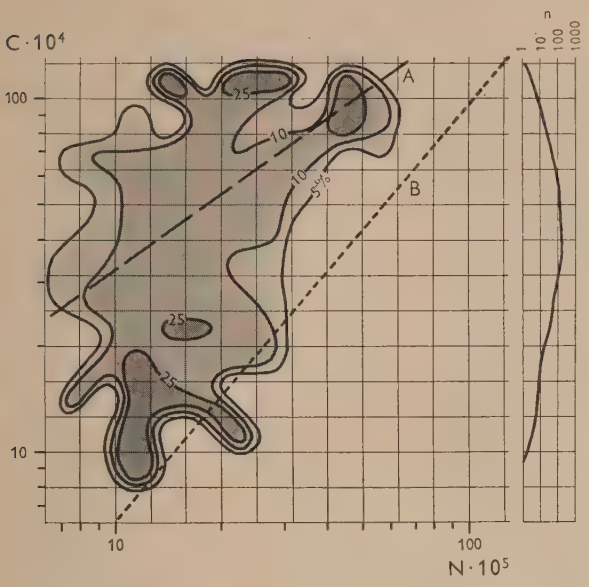

Fig. 1.4.3.5. The carbon-nitrogen relationship in East Eupelagic calcareous sediments. There is almost no correlation between the two properties within this facies. Samples with a high total rate of accumulation are concentrated in the upper part of the distribution body and those with a low total rac (marl oozes and clays) in the lower part.

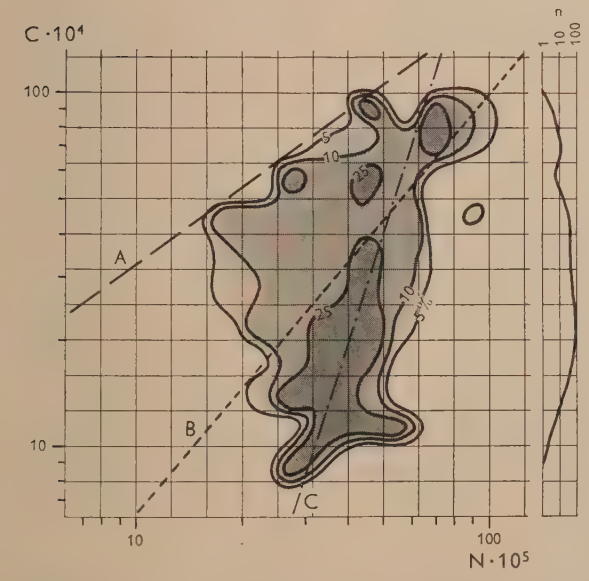

Fig. 1.4.3.6. The carbon-nitrogen relationship in North Equatorial pelagic clays. The samples are very rich in nitrogen, the correlation between the properties is poor and the regression which can be traced (equation line C) is due to the effect of ageing (recent sediments in the upper right, oldest sediments (Pliocene?) in the lower left part of the distribution body (cf § 1.4.4). For explanation of the lines A and B, see caption of fig. 1.4.3.4. The upper left edge of the distribution body is formed by samples from the North Equatorial silica facies, bordering the Equatorial carbonate area (fig. 1.0).

1.4.4 Posthume diagenetical changes of the organic matter.

Correns (1937), Revelle and Shepard (1939), and Wiseman and Bennett (1940) report a decreasing content of organic matter with depth in the sediment in short cores and ascribe this decrease to diagenetical decomposition of the organic matter. Correns, however, points out that contrary conditions also occur and that the influence of environmental changes cannot be excluded as an explanation of some cases of a downwards decreasing carbon content. In the long East Pacific calcareous cores investigated, the subsurface decrease of organic matter is often found but this appears in many cases to be an effect of the increased dilution with carbonate during the last Ice Age as the rac of carbonate is usually high in this stage, and as a high content of organic matter often returns in older carbonate minimum stages (cf pl. 2.58—2.62, 2.39, 2.42, 2.45, and 2.46). Lower Pleistocene and Pliocene calcareous sediments are found to be low in carbon and nitrogen but it is generally difficult to tell whether this is due to a lowered rate of deposition or to secondary decomposition.

In some cases a regular decrease of the nitrogen content with depth is observed to be superimposed upon the primary distribution. The best examples of this phenomenon are found in cores 45 and 46 (pl. 2.45 and 2.46). In these cases it is believed to be fairly certain that the slow, regular downwards decrease of the average nitrogen content is due to secondary decomposition of the organic matter. There is no contemporaneous decrease of carbon in these cores and the ratio C/N thus rises with depth in the sediment. Very low nitrogen contents associated with normal carbon contents are also found in the calcareous Tertiary sediments in core 53, 56 and 57. These conditions are contrary to those found in clay and silica facies and which are referred to below.

In the North Equatorial clay and siliceous

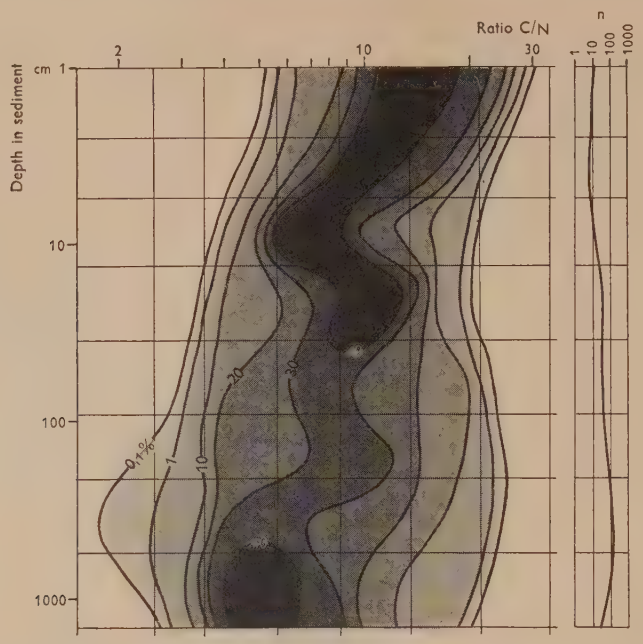

Fig. 1.4.4.1. The ratio carbon/nitrogen as function of depth in North Equatorial clay and siliceous clay cores. Both the carbon and the nitrogen contents are subject to a slow postdepositional decrease due to decomposition of the organic matter. Carbon, however, disappears from the sediment more rapidly than does nitrogen and as a result the ratio C/N decreases downwards.

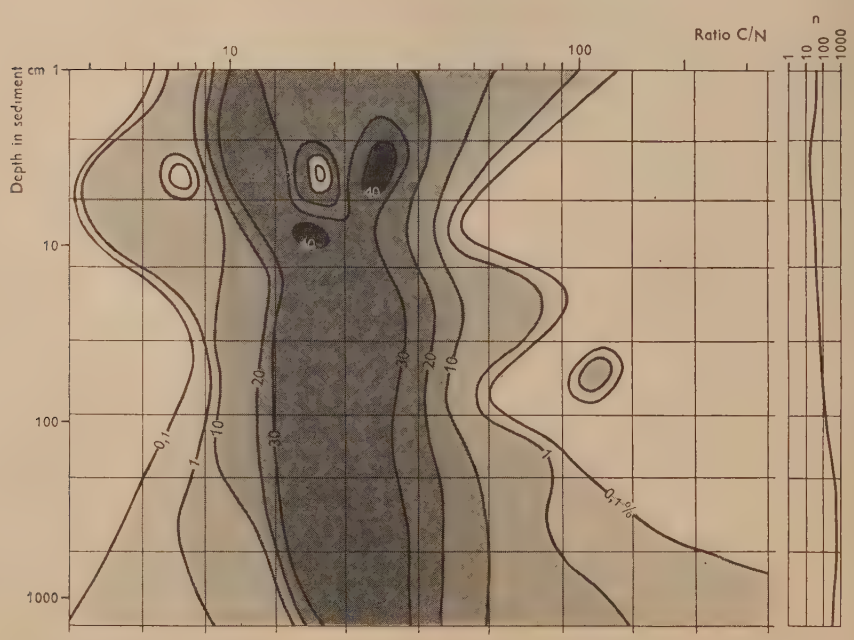

Fig. 1.4.4.2. The ratio carbon/nitrogen as function of depth in East Pacific calcareous sequences. The effect of ageing which is marked in clay and silica facies cannot be traced here. The distribution is irregular and patchy due to the influence of the environmental changes upon the deposition and decomposition of organic matter.

clay cores, which are unstratified with regard to calcium carbonate and where the total rate of accumulation is low, a definite decrease with depth both of carbon and nitrogen is often traceable (pl. 2.48—2.54), and it is obvious that the carbon content is more rapidly decreasing than the nitrogen content. As a result there is a marked linear logarithmic decrease of the ratio carbon/nitrogen with depth in the sediment (fig. 1.4.4.1). This effect is not traceable in the East Pacific carbonate cores (fig. 1.4.4.2), where the values are widely scattered due to the influence of other variables than time. The fact that these cores do not penetrate as far back in time as the clay cores, might contribute to the absence of the type of secondary changes which appear to be characteristic of pelagic clay sediments. The conditions found in cores 45, 46, 53, 56 and 57 and referred to above indicate that the diagenesis of organic matter taking place in calcareous sediments proceeds in a different way than in calcium carbonate-free deposits.

1.5 Phosphorus

1.5.1 Previous work.

The phosphorus content of pelagic deposits was investigated a. o. by CORRENS (o. c.) and REVELLE (o. c.). The precipitation of phosphorus in the form of phosphatic nodules was investigated by DIETZ, EMERY, and SHEPARD (1942) and by EMERY and DIETZ (1950). The cycle of phosphorus in the sea has been surveyed by SVERDRUP e. a. (1946) and by RANKAMA and SAHAMA (1950).

CORRENS demonstrated that the calcium carbonate deposited in the form of calcareous skeletons of planktonic organisms is associated with appr. $8 \cdot 10^{-4}$ P_2O_5, and that the phosphorus is largely retained in the sediment if the carbonate is dissolved. REVELLE indicated that in calcareous sediments from the South-East Pacific there is a close relationship between the concentrations of phosphorus and manganese. GOLDSCHMIDT (1922) indicated that the deep water of the oceans is enriched in phosphorus and represents a blind alley in the cycle of this element. DIETZ, e. a. and EMERY e. a. likewise pointed out that the sea water below the euphotic layer is probably saturated with phosphate, and that a precipitation must be assumed to take place, balancing the inflow of phosphorus dissolved in river water. KRUMBEIN and GARRELS (1952) have demonstrated that inorganic precipitation of phosphorite from normal sea-water as a result of a pH increase would be expected to yield a great amount of calcite and a very small proportion of phosphorite. The precipitation of phosphate suggested by GOLDSCHMIDT, DIETZ, e. a. (o. c.) mayt herefore be caused by organic agents or in some pelagic deposits by adsorption to manganese and iron compounds at the surface of the sediment. According to RANKAMA and SAHAMA redistribution of phosphorus in sediments might be caused by ammonia liberated from decaying marine organisms.

1.5.2 Distribution of phosphorus in pelagic clays.

The details of the distribution of phosphorus in pelagic clays and siliceous clays are put forth in § 2.48.5—2.57.5 and pl. 2.48—2.57, col P_2O_5. A synoptical survey of the frequency distribution of concentration of phosphorus is given in fig. 1.5.2.1. From this is seen that the distribution is very heterogenous with frequency maxima occurring in all classes, from 20—30 to 150—160 $\cdot 10^{-4}$ P_2O_5. The average content in igneous rocks amounts to $28 \cdot 10^{-4}$ P_2O_5 (CONWAY 1945) and in shales to $17 \cdot 10^{-4}$ P_2O_5 (STOKES and STEIGER, quoted from CLARKE, 1924). As has been indicated by previous authors, the phosphorus content of pelagic clays is thus seen to be considerably higher than that of igneous rocks. The Late Cenozoic average for North Pacific clays appears to be at least wice as high as the average given by CLARKE (o. c.) for red clay ($30 \cdot 10^{-4}$ P_2O_5).

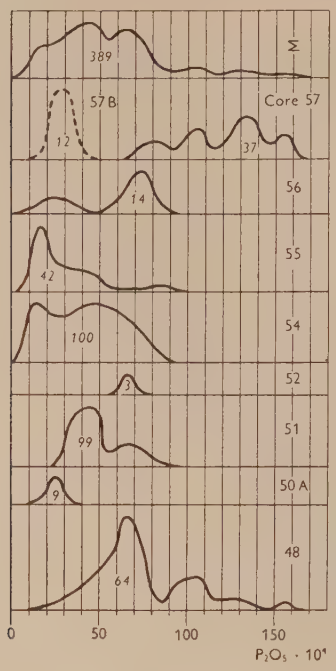

Fig. 1.5.2.1. Frequency distribution of phosphorus concentration in pelagic clays. The total number of samples is indicated below the curves. Each diagram accounts for the samples from one core, the number of which is indicated in the right part of the diagram. The top diagram shows the distribution in the entire North Equatorial clay area. The grid corresponds to the class interval; $10 \cdot 10^{-4}$ P_2O_5.

Clarke's average is representative of the Pleistocene clay deposits of the North Equatorial Pacific (pl. 2.48—2.57, upper part of the sequences). The frequency maxima in high, and very high concentrations (fig. 1.5.2.1) are caused by Tertiary strata rich in phosphorus. The stratigraphical distribution of these is seen from fig. 1.5.2.2. In the Calcareous Tertiary the concentration of phosphorus recalculated on the noncalcareous component is appr. 1 %, and the values below $50 \cdot 10^{-4}$ P_2O_5 in core 53 (fig. 1.5.2.2) are caused by dilution with calcium carbonate. The concentration in the phosphatic members P2, P4 and P6 does not exceed $90 \cdot 10^{-4}$ P_2O_5 and the average content of the members P 1, P 3 and P 5 is $30—40 \cdot 10^{-4}$ P_2O_5. Core 52 is abnormal (local volcanism) and the high phosphorus content is associated with minerolytic manganese, apparently derived from weathering pyroclastics.

Two explanations might be offered with regard to the formation of the phosphatic Tertiary strata: the rate of accumulation of phosphorus may have increased or the rate of accumulation of lutite may have decreased. As possible causes of an increased rac of phosphorus might be suggested: 1) an increased supply of phosphorus from the continents, 2) a change of the physico-chemical environment as to favour inorganic precipitation of phosphorite (increased pH and temperature), 3) an increased rate of organic precipitation or inorganic adsorption of phosphorus. The first alternative will be discussed later in this paragraph. Alternative 2 would according to Krumbein and Garrels (o. c.), require simultaneous precipitation of great amounts of calcium carbonate and is therefore excluded. The third alternative would imply an increased transport of phosphorus to the sea bottom in the form of organic detritus and in skeletal structures, later dissolved; or an increased deposition of manganese and (or) iron, or possibly in an increased fixation of phosphorus by the activity of mud-eating animals. (Analyses of faecal pellets from core 45 did not, however, indicate any enrichment of phosphorus). All these possibilities, included in the third alternative appear, however, less probable when confronted with the supply requirements. The work of previous authors indicates that the sea is saturated with phosphate and that an amount equal to the increment is precipitated each year. If alternative 3 is applied, the theoretical maximum amount of phosphorus available at an increased accumulation of this element is the total amount dissolved in the sea + the increment from the continental waters. In reality a complete depletion of phosphorus from the sea is an absurdity, and it would even involve an enormous change if the total amount of phosphorus present in the sea were decreased

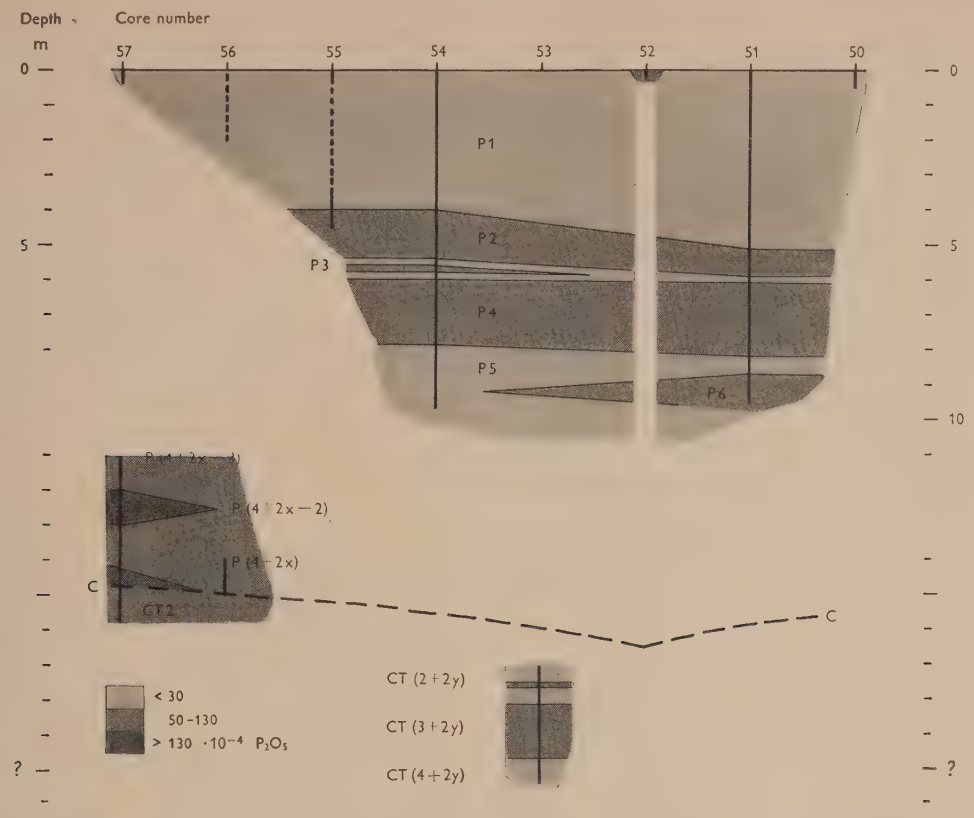

Fig. 1.5.2.2. Stratigraphy of the present North Equatorial clay area. Vertical lines correspond to sediment cores. The core number is indicated at the top of the figure. Core 52 is situated furthest to the north (fig. 1.0), cores 53—57 are distributed SSW and cores 51 and 50 SE of core 52. C is the presumably metachronous Upper Tertiary level of transition from calcareous ooze to clay (= the calcium carbonate compensation surface, cf. ch. 1.1 and § 3.3.2). The subdivision in P-members is based on the phosphorus content of the deposit (indicated by the surface shade in the diagram), and in CT-members on the content of calcium carbonate (pl. 2.53, 2.56 and 2.57). The upper parts of cores 55 and 56 were distorted at sampling and the exact thickness of the member P 1 is, therefore, not known in these cores. Core 52 is abnormally rich in phosphorus, which is supposed to have been concentrated by precipitation on minerolytic manganese oxidates from volcanic debris (ch 2.52).

to half the original value. According to SVERDRUP e. a. (o. c. p. 182) the maximum content of phosphorus in sea-water is appr. 3 μg-atoms/L. As an average might be taken 2.3 μg-atoms/L (cf SVERDRUP e. a., o. c. fig. 48), which corresponds to the same amount in a 10 m high column with a cross section of 1 cm². A column with this cross section and extending to the bottom at 4 500 m, would contain appr. 1.04 mg-atoms of phosphorus or appr. 70 mg P_2O_5. If half of this amount, 35 mg P_2O_5, were extracted from the sea water and transported to the bottom, it would increase the normal concentration of $30 \cdot 10^{-4}$ P_2O_5 to $60 \cdot 10^{-4}$ (which is representative of the phosphatic members) in 12 g of dry sediment. A square cm column of pelagic clay with this content of dry matter has an approximate length of 36 cm. As the phosphatic strata have a thickness of one to several meters, it is obvious that even a complete depletion of the phosphorus, would not be sufficient to explain the increased phosphorus content of the phosphatic Tertiary strata, if it is not assumed that the North Equatorial Pacific was an area of preferred deposition of phosphorus during the time intervals in question. The Equatorial carbonate area (§ 1.5.4) is at present, and was especially during the Ice Ages, such an area of preferred phosphate deposition, but there

is no reason to assume this in the present case.

As an increased rate of accumulation of phosphorus without an increased supply from the continents apparently fails to explain the formation of the phosphatic Tertiary strata, it is most probable that these were laid down in connection with a high rate of transport of phosphorus to the sea, possibly combined with a low rate of minerogenous accumulation. In other words, the Late Cenozoic stratification of the pelagic clay deposits of the North Equatorial Pacific probably indicates that in Tertiary time the chemical denudation of the continents was of comparatively great importance so that the amount of dissolved matter carried to the sea was greater. This might be a consequence of the Tertiary climatic conditions which certainly favoured weathering on the continents.

In connection with the climatic change which appears to have taken place in the Upper Tertiary and which led to the lowering to zero of the calcium carbonate accumulation in the North Equatorial Pacific (metachronous level *C* in fig. 1.5.2.2), there followed a series of ages with a decreased concentration of phosphorus in the pelagic clay (members P 4 + 2 x — 1, P 4 + 2 x — 3,. . . . . ., P 5 and P 3 in fig. 1.5.2.2) alternating with reversions to conditions similar to those prevailing in older ages, although not so strong as to lead to accumulation of calcium carbonate. These ages are represented by the stages P 4 + 2 x — 2, ..., P 6, P 4 and P 2. The stages with a decreased content of phosphorus might possibly correspond to ages with a reduction of the zones of tropical weathering and consequently with a decreased transport of solutes to the ocean and possibly with a slight change in the density of the lutite veil for reasons treated in the following.

Finally, the climatic development is believed to have led to the definite transition from accumulation of phosphatic clay (stage P 2) to deposition of the pelagic clay, relatively poor in phosphate, which characterizes the thick top stratum P 1, extending into Recent. The present eupelagic rate of accumulation in the East Eupelagic area corresponds to appr. 0.28 cm/1 000 years and the member P 1 is assumed to comprise appr. 1.3—1.7 million years, i. e. Pleistocene and the last stages of Pliocene as defined in the present work (§ 2.58.13 and § 3.1). The definite transition to Pleistocene weathering conditions thus probably took place in the last stages of Upper Pliocene.

It appears impossible at the present moment to estimate quantitatively the relative importance of the changes in transport of silicate hydrolyzates from the continents to the pelagic environment on the one hand and of dissolved and colloidal phosphates on the other. Qualitatively it may, however, be assumed that the latter factor is subject to the greatest changes when that area of the Earth, which is subject to extensive chemical denudation, is changed. The first factor is supposed to be dependent not only on the rate of mechanical denudation of the continents, but also on the state of comminution of the mechanically disintegrated material, as only the finest fractions of the hydrolyzates might be expected to accumulate in the pelagic environment. In the cold regions, mechanical weathering is certainly of greater importance than in the warm, humid region, but the debris prevails largely as resistates (according to Goldschmidt's classification, modified by Rankama and Sahama, 1950), which are almost completely retained on the continental shelves. In the warm, humid region hydrolyzates dominate the debris, which is therefore expected to contribute largely to the pelagic lutite. The Late Pliocene and Pleistocene expansion of the temperate and cold regions of weathering is believed to have resulted in a decreased net transport of dissolved and colloidal phosphates and of oxidates to the sea and in a greater net transport of solid matter from the continents, but it is questionable

whether the supply of silicate hydrolyzates to the lutite veil (cf. ch. 1.2) and finally to the pelagic environment of deposition, increased, decreased, or was approximately constant. As another cause of increased supply of lutite to the ocean might be suggested tectonic rejuvenation of the erosion in regions of warm humid weathering. It appears, however, less probable that locally or regionally limited tectonical events had any considerable influence on the Late Cenozoic density of the lutite veil particularly as a rejuvenated erosion in one region might be balanced by topographical maturity in another.

The eustatic lowering of the sea level during the Ice Ages is believed to have caused erosion of shelf sediments. This appears to have resulted in redeposition and transport of residuates to the continental slope and possibly in a slight increment of the rate of transport of lutite to the pelagic environment. The changes in phosphate content recorded in the Upper Pleistocene part of the member P 1 might partly have been caused by this effect, partly by changes in the chemical denudation, brought about by the alternation between Glacial and Interglacial type of weathering. During the Ice Ages the supply of eolian lutite might further have been of increased importance. The Tertiary stratification of the pelagic clays with regard to phosphorus, however, appears to be most easily explained if changes in the supply of dissolved and colloidal phosphate to the ocean are assumed. The increased content of halmyrogenous manganese and iron in the phosphatic strata indicates that these elements were also supplied in greater quantities to the ocean during ages of increased transport and accumulation of phosphorus in the oxidizing pelagic environment.

Although greater probability can thus be ascribed to one of the alternatives suggested as explanations of the high phosphorus content of the Tertiary strata, this explanation has to be regarded as tentative.

1.5.3 Distribution of phosphorus in the calcareous East Pacific Ridge sediments. Association with manganese.

The distribution of phosphorus in the sediments from the East Pacific Ridge (§ 2.38.5—2.47.5) is heterogenous and confirms the varying conditions of deposition in this area. In addition to the factors indicated in the preceding paragraph, the concentration of phosphorus in these deposits is believed to be determined by 1) the phosphorus content of the minerogenous source material, 2) the concentration and state of dispersion of manganese and iron compounds in the sediment surface, 3) the dilution with biogenous matter and 4) the chemical redistribution of phosphorus within the sediment. The effect of the first factor, possibly combined with the second is illustrated by cores 38—40 from the Galapagos area, which are abnormally low in phosphorus (§ 2.38.5—2.40.5) as compared with other deposits from the East Pacific Ridge.

The association of phosphorus with manganese appears to be brought about by two processes. Firstly, both phosphorus and the manganese oxidates brought to the sea in dissolved and suspended form, are largely deposited together in the oxidizing pelagic environment (§ 1.5.2 and 1.12.6). This genetical type of manganese is here called halmyrogenous (§ 1.12.6). Secondly, especially in regions of volcanic activity, considerable amounts of manganese appear to be released by the submarine weathering of igneous rocks and to be separated from iron through selective diffusion and precipitation (§ 1.12.6). This genetic type is here designated minerolytic manganese.

In the East Pacific Ridge sediments, the manganese is believed largely to be of minerolytic origin and the rate of accumulation of this element is mostly many times higher than in the eupelagic environment. These manganese-rich sediments are abnormally rich in phos-

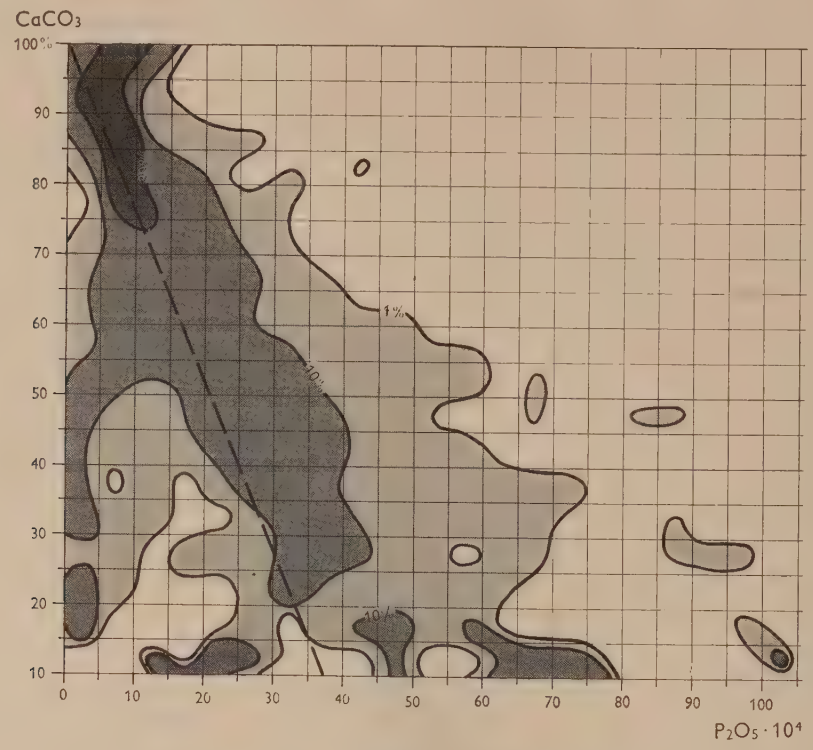

Fig. 1.5.3. Relation between calcium carbonate and phosphorus concentration in all calcareous East Pacific sediments. Owing to the irregularities in the composition of the minerogenous matter, rate of dissolution of calcium carbonate, redistribution of phosphorus in the sediment, and supply of minerolytic manganese and iron, the scattering of the values is very high in the East Pacific Ridge sediments and as a consequence in the entire population. The abundance of minerolytic manganese in the East Pacific Ridge area causes a displacement of the average regression line to the right of the East Eupelagic average (dashed line) even in samples with the highest carbonate contents. The distribution ridge in very low phosphorus and intermediate carbonate contents is caused by the samples from the Galapagos area. The location of the samples from each core separately is shown in fig. 2.38.5—2.47.5 and 2.58.5—2.62.5. The course of the isopleths at the lower edge of the diagram is determined by the frequency distribution in the North Equatorial clay area.

phorus (see below and § 2.41.5—2.47.5), as was indicated by Revelle (o. c.). It is believed that the manganese hydroxide sol and gel present in the deposit precipitates phosphorus from the sea water in contact with the sediment surface, hereby increasing the phosphorus content of the deposit. As the manganese hydroxide sol is negatively charged (Rankama and Sahama 1950), the fixation of phosphorus is believed to take place as precipitation due to the low solubility of manganese phosphates, rather than as adsorption. The iron hydroxide sol and gel present in the sediment certainly contributes to the fixation of phosphorus, which might in this case also be adsorptive, as suggested by Correns (1937, p. 228).

The third effect, indicated in the beginning of this paragraph, viz. the dilution with biogenous matter, is of great importance for the final concentration of phosphorus in the East Pacific sediments. The relation between calcium carbonate and phosphorus concentration is shown in fig. 1.5.3. From this graph is seen that there is a general increase in phosphorus content with decreasing carbonate content, but the scattering is considerably higher than in the East Eupelagic area (fig. 1.5.4.1). As in the latter region, part of the scattering is due to varying amounts of biogenous silica present in the samples, but this effect explains only relatively small deviations from the eupelagic average, represented by the

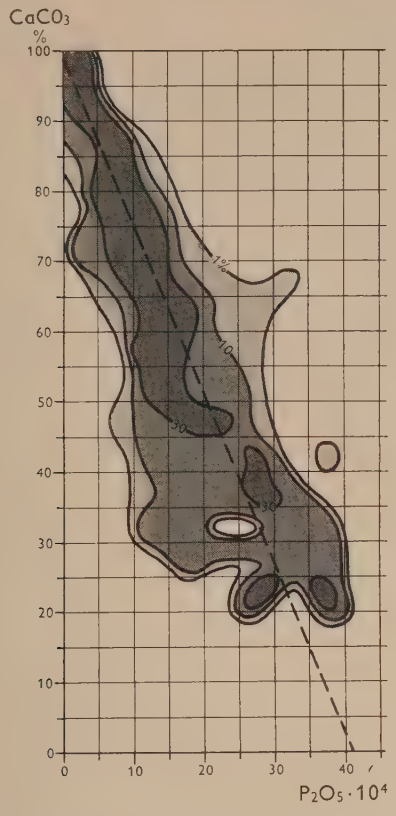

Fig. 1.5.4.1. Relation between calcium carbonate and phosphorus concentration in the East Eupelagic area. Most factors complicating this relationship in the East Pacific Ridge sediments are absent in the eupelagic environment and the deviations from the estimated average (dashed line) are mainly caused by varying dilution of the sediment with biogenous silica.

guide line. The great deviations from this line are believed to be caused by the factors mentioned above. The relation $CaCO_3$ — P_2O_5 is treated in each core separately (§ 2.38.5—2.47.5.)

1.5.4 Distribution of phosphorus in the East Eupelagic carbonate area.

In the eupelagic environment the distribution of phosphorus appears to be more simple than on the East Pacific Ridge. This is understandable as many complicating factors have disappeared in the eupelagic environment. The minerogenous matter is very homogenous with regard to distribution, rate of accumulation and composition and consists almost entirely of hydrolyzates which cannot give rise to minerolytic manganese and phosphorus. These elements are therefore believed to be almost completely halmyrogenous in the East Eupelagic area, and the correlation between phosphorus and calcium carbonate is much closer (fig. 1.5.4.1) than in the total East Pacific material (fig. 1.5.3). Fig. 1.5.4.1 indicates that the calcium-carbonate-free sediment has an approximate concentration of $42 \cdot 10^{-4}$ P_2O_5, which decreases with an increasing admixture of calcium carbonate.

As is seen from fig. 2.58.5—2.62.5 there are within the different eupelagic cores systematic deviations from the average distribution shown in fig. 1.5.4.1. These deviations are most marked in samples with a low carbonate content. Cores 58 and 62 are thus higher in phosphorus than the eupelagic average, 59 is low and 60 and 61 are very low. These deviations might theoretically be assumed to be caused by dilution of the sediment with biogenous silica, which is poor in phosphorus.

In order to check this possibility and to investigate the significance of the distribution shown in fig. 1.5.4.1 and in fig. 2.58.5—2.62.5, the distribution of the rate of accumulation of calcium carbonate was calculated as a function of rac of phosphorus (fig. 1.5.4.2). This distribution is not influenced by variations in the admixture of biogenous silica, if this is free from phosphorus. Most of the deviations referred to above have disappeared in fig. 1.5.4.2, thus increasing the probability that the suggested explanation is correct. A small number of samples, however, remain abnormally low in phosphorus and form the branch extending to the left from the lowest part of the distribution body. This branch consists of the samples 50, 70 and 130 from core 58, which form an isolated group in the bottom of the graph 2.58.5, and of 400, 408 and 517 in core 60, which form the group at the bottom of fig. 2.60.5. The deviation of these samples cannot be explained by dilution with biogenous silica, but is probably due to secondary redistribution of phosphorus (cf § 2.58.5 and 2.60.5).

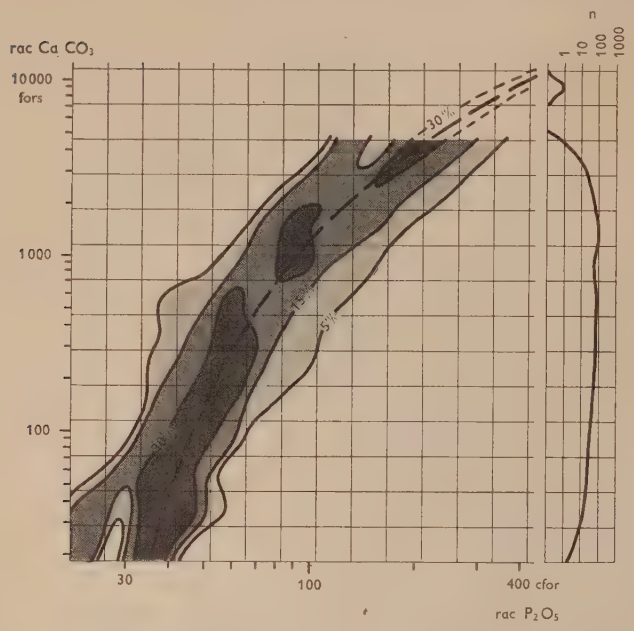

Fig. 1.5.4.2. Relation between rac $CaCO_3$ and rac P_2O_5. The dashed line corresponds to the estimated regression.

The estimated regression curve of the logarithmic distribution shown in fig. 1.5.4.2 has been redrawn in arithmetic scale in fig. 1.5.4.3. From this is seen that in intermediate and high rates of accumulation there is an apparently linear relationship (rac $CaCO_3 = 3\,030 \cdot$ rac $P_2O_5 - 1\,990$), but in low rates of accumulation the relationship is curved. An enlargement of this latter part of the diagram is shown in fig. 1.5.4.4. The value of rac P_2O_5 for rac $CaCO_3 = 0$ cannot be obtained from fig. 1.5.4.2, but is extrapolated from fig. 1.5.4.1. The curvation of the relationship between rac $CaCO_3$ and rac P_2O_5 indicates that when the rate of biogenous accumulation is low and decreases, the proportion of phosphorus to calcium carbonate is more and more rapidly increased. This is believed to be due to the effect, indicated by CORRENS (1937, p. 223 and 230), that the phosphorus compounds, because of their lower solubility, are enriched at the dissolution of the calcium carbonate. The rate of dissolution of calcium carbonate tends to increase when the total rate of deposition is decreased (§ 1.1.2) and thus when the rac of $CaCO_3$ approaches zero, larger and larger amounts of calcium carbonate have been dissolved from the sediment and the sparingly soluble constituents of the biogenous matter (e. g. biogenous silica and phosphorus) have been more and more enriched. These conditions might offer a possibility for a future quantitative study of the dissolution of calcium carbonate. This, however, is possible only if the relationship between rate of deposition of calcium carbonate and rate of deposition of phosphorus can be determined and if the rate of dissolution of phosphorus under varying

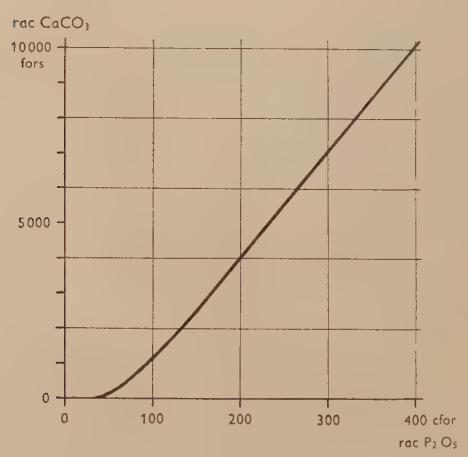

Fig. 1.5.4.3. The regression line of fig. 1.5.4.2, redrawn on arithmetic scale.

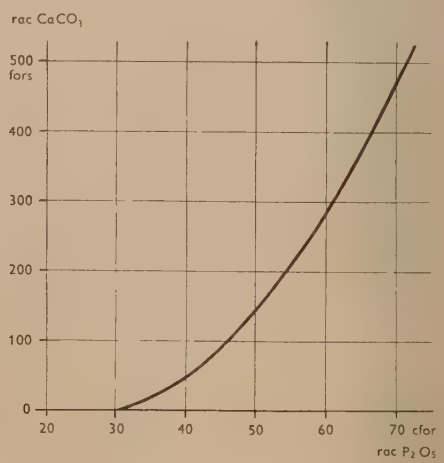

Fig. 1.5.4.4. Lower part of curve shown in fig. 1.5.4.3.

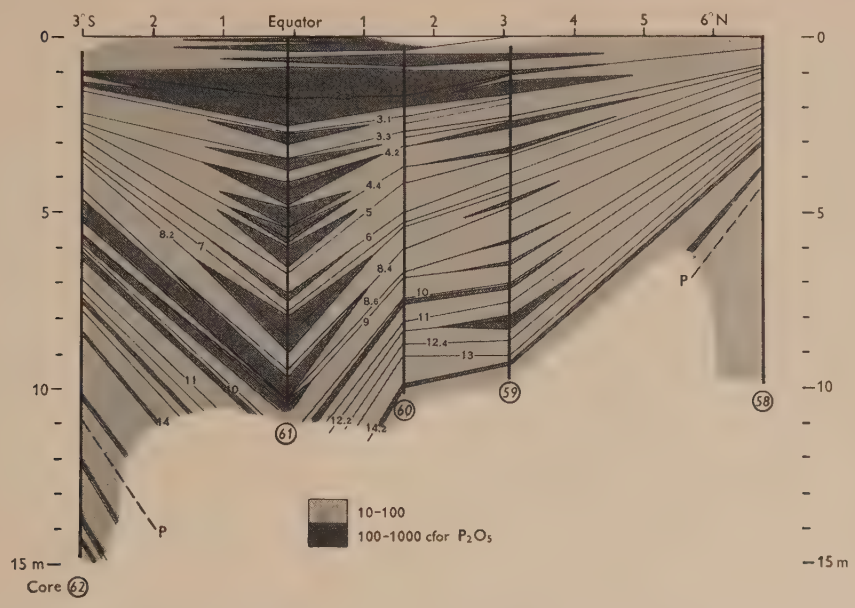

Fig. 1.5.4.5. Rate of accumulation of phosphorus in the East Eupelagic carbonate section (cf fig. 1.0). Vertical lines correspond to the sediment cores, the number of these being inserted in the lower part of the diagram. The numbers of the stratigraphical units and the location of their centers are indicated in the figure. The distribution obtained corresponds closely to the distribution of rate of accumulation of calcium carbonate and biogenous silica (fig. 1.1.6.1 and 1.3) and thus generally to the distribution of rate of production in the sea. The highest rac of phosphorus is found in core 61 below the Equatorial Divergence and in the stages and substages which correspond to an increased rate of circulation and production. A feature which deviates from the general distribution of rate of biogenous accumulation is the very high rac of phosphorus in the last circulation maximum (stage 2) in comparison with the penultimate circulation maximum (stage 4), which is unsurpassed with regard to rac of calcium carbonate, total biogenous silica and diatoms.

conditions is known. Complications might also be caused by postdepositional redistribution of phosphorus.

1.6 Colour and pattern

1.6.1 Scope and limitation of the investigation.

The system of W. Ostwald (ref. in part 4) was used for the description of colours. The colour theory of Ostwald suffers from some weaknesses (Bouma, 1944), which do not, however, influence the value of the colour standards for reference purposes. Ostwald's system was chosen because of its simplicity and its suitability for graphical representation of the distribution of colour in sedimentary sequences. In the Ostwald system, the colours are distributed along the equator of a double cone, the axis of which is formed by the black-white scale. A radial section through the cone from a point c on the equator to the axis represents a ternary diagram illustrating the amount of colour of the hue c, the amount of black and that of white of any point situated in it. According to Ostwald's theory a colour is uniquely defined by the hue (location of the section on the equator), the amount of black and the amount of colour (shade). The quantitative meaning of the symbols, indicating these properties, is mentioned in the description to the tables of vol. 2, (appendix vol 2).

Difficulties in the definition of the colour of normal pelagic deposits arise from the inhomogeneity with regard to colour which is caused by digging structures and reduction bodies. The values indicated in pl. 2.39—2.62 refer to what is estimated to be the dominating colour but it is often very difficult to determine which is the dominating one of several colours in a complicated pattern (cf. pl. 2.6.1—2.6.10).

As a result irregular curves are obtained in such cases but the irregularity reflects to some extent the heterogeneity of the pattern of the sediment.

1.6.2 Significance of colour.

A survey of the significance of the colour of marine sediments has been given by REVELLE (o. c. p. 5—6). The experiences gained from the present material agree with the general statements put forth by REVELLE.

The hue of the East Pacific sediments varies mainly from greenish yellow to red. Greenish hues are met with in the Galapagos area, where they are not masked by ferric-manganese oxidates and where the content of organic matter is high. The greenish colour might either be due to organic compounds or to ferrous iron which might be stable in this environment because of the high rate of accumulation and presumably because of a low reduction-oxidation potential made possible by the high content of organic matter. Yellowish grey appears to be the normal lutite colour. Red hues are connected with ferruginous sediments and the amount of black is high when the concentration of manganese oxidates is high. It should be pointed out that variations in hue and blackness of deposits rich in manganese and iron oxidates are brought about not only by variations in the concentration of these compounds but also by changes in their state of dispersion. Deposits rich in iron and manganese are thus sometimes found to be comparatively light coloured, viz. when the elements in question are concentrated to nodules.

The hue of very pure chalk oozes is poorly defined. In such sediments small amounts of finely divided manganese might give rise to an apparently blueish hue (core 61).

The blackness of the sediment appears to be a complex function of the content of dark components of the organic matter, of manganese oxides and of the state of dispersion of these. The East Pacific sediments are never very bright coloured and the shades mostly vary between *a* and *g*. The brightest shades seem to occur in such reduction structures of sediments originally rich in minerolytic oxidates, where manganese has been largely removed and much of the iron oxides are left in a whitish carbonate-lutite matrix (§ 2.45.6).

1.6.3 Pattern of East Pacific deposits.

Typical patterns observed in the East Pacific cores are illustrated by pl. 2.6.1—2.6.10.

With regard to the details of the photographs of cores shown in pl. 2.6.1—2.6.6 the reader is referred to § 2.38.6—2.62.6. The survey pictures in pl. 2.6.1—2.6.6 have been selected to illustrate typical features such as reduction bodies, digging structures, chert laminae, unconformities, etc. Microlamination, apparently caused by short-distance transport and precipitation of manganese, is illustrated by core 61. Although the mass transport appears to be extremely small in this core, the lamination is very obvious, depending on the white colour of the background sediment. The microlaminae pass through the digging structures, which proves them to be of posthume origin.

A series of detail pictures (prepared from 9×12 cm colour slides) are shown in pl. 2.6.7—2.6.10. These detail pictures are labelled with the core number and the depths in cm from the top of the core to the upper edge of the photograph. *39 502—514* shows some details of the reworking pattern of core 39 (s. survey photograph in pl. 2.6.1). A structure of the type 40—873 x (cf. § 2.40.6) extends between 507 and 508 cm. The lower surface of this structure with typical parallel striation is shown in a cross section of the core at 508 cm (detail figure *39—508*). Other examples of this phenomenon are shown in the detail-fig. *40 872—883*.

41 323—334 shows the silica front at 329 cm, referred to in § 2.41.6, with surrounding sediment. The lamina 329—329.5 cm is very

strongly indurated (cf. pl. 2.41, col. 100 · log H). The detail-fig. *41 418—430* contains two additional examples of extensively silicified strata, one extending from 420 to 421.7 cm and displaying an internal lamination. The other is located between 427 and 429 cm and is hardly visible, although the strength is extensively increased.

41 520—532 Bent and dislocated laminae above clay breccia.

42 548—560 Dark, hard, silicified laminae.

43 788—800 Reduction body of unusually large size.

45 775—787 Cavity fillings or clay balls (structure of uncertain origin). S. f. end of § 2.45.6.

48 464—476 Horse-shoe and eye structures (reduction bodies).

52 000—012 Manganese crust resting on clay.

56 000—010 Erosional unconformity between Late Pleistocene and Tertiary (presumably Pre-Pliocene).

58 702—714 and *58 940—952* Reworking structures in the Late Pliocene strata of core 58.

59 466—478 Reworking structures, including a longitudinal section of a filled worm hole with an unusually great depth of penetration.

60 610—622 Reworking structures and slightly diffused stratum boundary. The downward bending of the structures is caused by the corer.

61 331—343 and *61 468—480* Reworking structures and slightly diffused stratum boundaries.

62 1001—1013, 62 1078—1090 and *62 1150—1162* Reworking structures and diffused stratum boundary.

62 1430—1442 Reworking structures.

1.7 Foraminifera

1.7.1 Aims and scope of the investigation.

As has been pointed out in § 4.9.1 the present study of foraminifera aims in the first place at investigating the petrographical relationships between concentration of foraminifera and other properties of the sediment and at elucidating the significance of these relationships with regard to environment of production, deposition, and diagenesis. Parallel to these investigations was recorded the percentage composition of the fauna, and the benthonic foraminifera were isolated for closer study. The taxonomical classification method was designed by F. Brotzen and the subdivision was not carried further than that it could be undertaken by non-academically trained assistants. For details of the methods used, see ch. 4.9.

1.7.2 Concentration of foraminifera.

One of the first systematic investigations of the concentration of foraminifera in pelagic deposits was carried out by W. Schott (1935) in connection with his investigation of the sediments collected by the German Atlantic Expedition with the »Meteor». Schott determined the weight of a known number of washed and sieved foraminifera and, using the result as a standard, he calculated the concentration of foraminifera in unknown sediments by weighing washed and sieved one gram samples and assuming that the fraction on the sieve was constituted entirely by foraminifera. The validity of this assumption was checked by microscopical analysis. The limitations and advantages of Schott's foraminiferal number have been indicated by Correns (1937, p. 206—207).

On account of the considerable and varying amount of remains other than foraminiferal tests in the fraction $> 150\,\mu$, Schott's method of estimation of the concentration of foraminifera could not be applied in the present material. In the present work the concentration of foraminifera was therefore estimated by counting the number of specimens in an aliquot part of a 1 g sample. The method is described in ch. 4.9. The concentration values obtained suffer from the

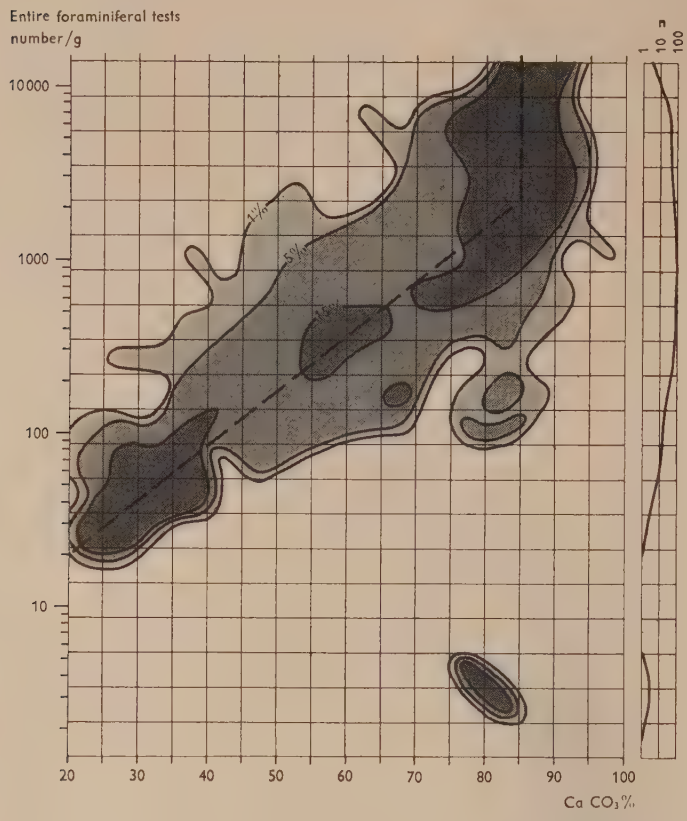

Fig. 1.7.2.1. Relation between concentration of entire foraminiferal tests > 150 μ and concentration of calcium carbonate in the East Eupelagic sediments. The inclined part of the guide line corresponds to the relationship; $\log n = 3.14 \cdot CaCO_3 + 0.67$, where n is the concentration of tests and $CaCO_3$ the calcium carbonate concentration. The protuberance from the right, lower part of the distribution body and the isolated group in the right lower corner of the graph, are formed by globigerina chalk ooze, rich in coccoliths and by coccolith chalk ooze.

same principal limitation as SCHOTT's, viz. that the fraction below the grain size limit used is not represented. The uncertainty arising from this was decreased by using a small minimum grain size, viz. 150 μ. The influence of the grain size limit on the results has been treated in ch. 4.9. Entire tests and fragments were recorded separately.

The relationship between the concentration of entire foraminifera and the content of calcium carbonate of the sediment is shown in fig. 1.7.2.1, including the East Eupelagic sediments. The inclined part of the guide line drawn in this graph corresponds to the approximate average relationship found in this area ($\log n = 3.14 \cdot Ca\,CO_3 + 0.67$). The distribution demonstrates that there is an approximate linear relationship between the logarithm of the concentration of foraminifera and the concentration of calcium carbonate. The dispersion of the values is, however, considerable. The reasons for systematical deviations from the average relationship will be treated in the following.

The average eupelagic relationship indicates that the concentration of foraminifera is doubled at each increase of 10 % of the calcium carbonate concentration. An increase of the carbonate concentration from 20 to 30 % is thus accompanied by an average increase of the concentration of entire foraminifera with 18 specimens, whereas an increase from 70 to 80 % $CaCO_3$ raises the number of entire tests per gram sediment by 590 specimens. The number of entire tests per unit weight of $CaCO_3$ is thus seen to increase considerably with increasing carbonate content and the calcium carbonate is more and more concentrated to entire foraminiferal tests. The reason for this is believed to be that the ratio entire tests/fragments increases with increasing rate of biogenous accumulation and thus with increasing carbonate concentration. Fig. 1.7.2.2 shows the concentration of entire foraminifera as a function of the concentration of fragments in the eupelagic sediments. This graph shows that, as the relationship conc. entire foram. — conc. $CaCO_3$ (fig. 1.7.2.1), the relationship conc. entire foram. — conc. fragments is not well defined above concentrations of approx. 1 000 entire foraminifera/g. The average approximate relationship between entire foraminifera and fragments in the area below this limit is; $\log f = 0.94 \cdot \log n + 1.42$ or $f = 26 \cdot n^{0.94}$,

where f is the concentration of fragments $> 150\,\mu$ and n is the concentration of entire tests $> 150\,\mu$. The relationship between the two variables is thus almost linear, and the slight increase of the ratio n/f indicated by the exponent is not sufficient to explain the rapid increase in the number of entire tests per unit weight of carbonate with increasing carbonate content. This might be explained in two ways. Either the average test weight is smaller when the carbonate content of the sediment is high (i. e. when the rate of accumulation is increased and the surface water cooled through upwelling) or the increase in the number of entire tests $> 150\,\mu$ per g $CaCO_3$ corresponds to a decrease in the carbonate mass fraction of fragments smaller than $150\,\mu$. The former alternative was tested by correlation of the number of tests $> 500\,\mu$ with the total number of foraminifera and was found to be unacceptable in the case of the eupelagic sediments. The latter alternative on the contrary is in agreement with qualitative checks of the grades finer than $150\,\mu$. Observations leading to similar conclusions were made by REVELLE (1944, p. 46).

The distribution of the entire East Pacific material is shown in fig. 1.7.2.3. This graph shows that if the entire material is taken into account, the dispersion of the relationship is very great and the estimated increase of the number of tests/g $CaCO_3$ with increasing content of $CaCO_3$ appears to be still higher than in the eupelagic area, which indicates that the comminution of the tests is usually very extensive when the rate of accumulation is low. The distribution coincides fairly well with that found by CORRENS (o. c.)

The phenomenon of fragmentation was studied by REVELLE (o. c.) who concludes (p. 121) that it might be explained by mechanical disintegration in the intestinal tracts of mud eating animals and by dissolution in the carbonic acid produced by the metabolism of animals and bacteria. This explanation appears

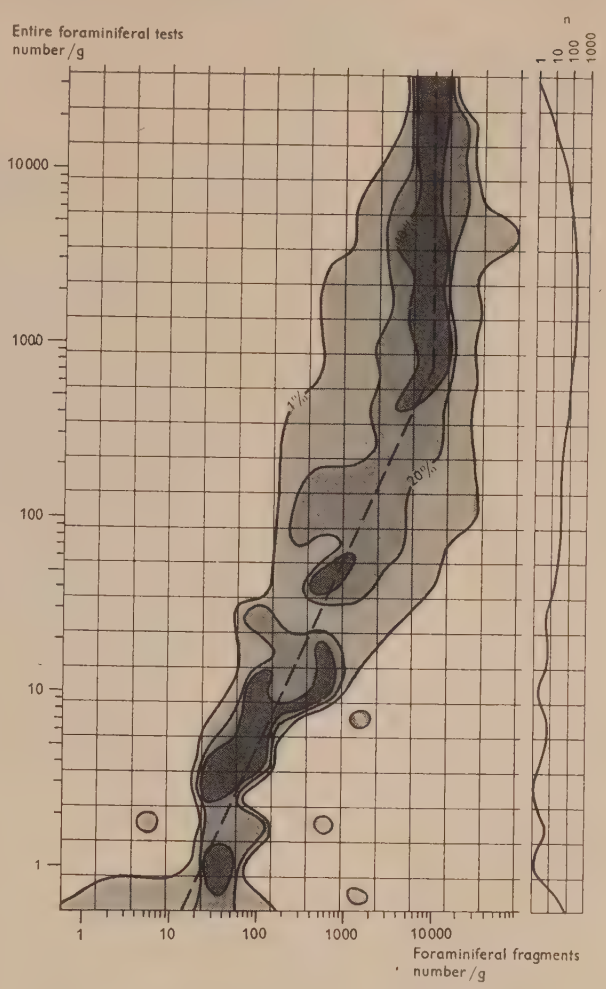

Fig. 1.7.2.2. Relation between concentration of entire foraminiferal tests $> 150\,\mu$ and foraminiferal fragments $> 150\,\mu$ in the East Eupelagic sediments. The inclined part of the guide line corresponds to the equation; $f = 26 \cdot n^{0.94}$ where n is the concentration of entire tests and f the concentration of fragments.

to be very probable as among the fragments some are relatively thick-walled and sharp-edged and others have corroded edges. Both types occur together. The increased comminution of the tests in connection with a lowered rate of accumulation is explained by the conditions of dissolution treated in ch. 1.1 and possibly also by the fact that during times of a low rate of accumulation the sediment was more extensively churned over by animals before being covered than during times with a high rate of accumulation.

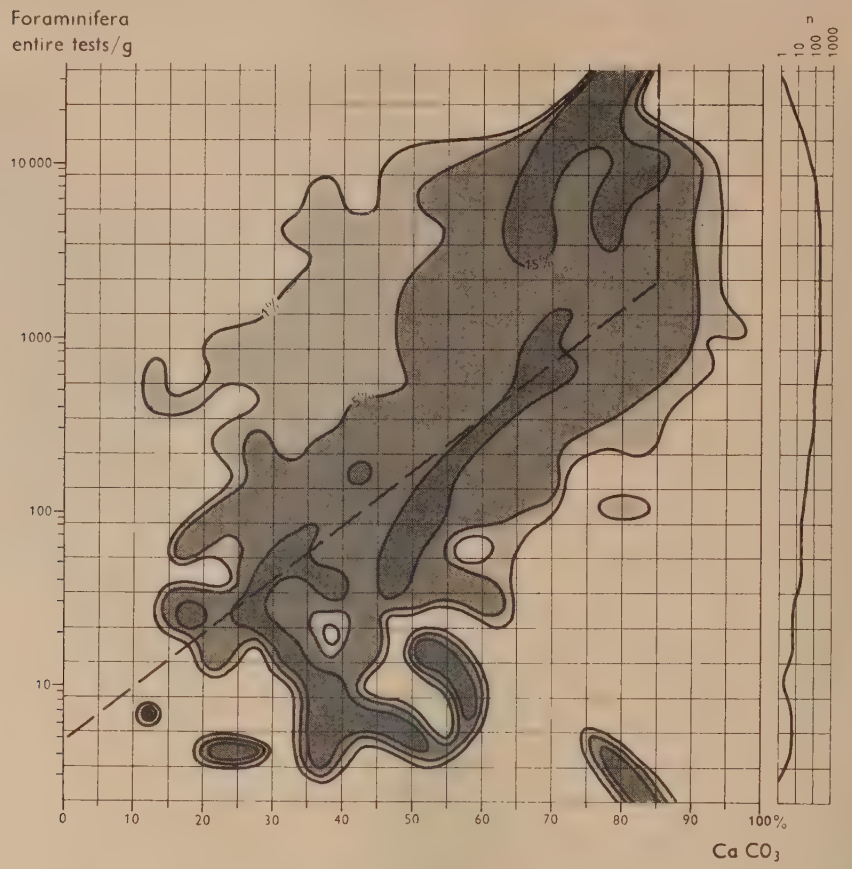

Fig. 1.7.2.3. Relation between concentration of entire foraminiferal tests > 150 μ and concentration of calcium carbonate in all calcareous East Pacific sediments. The guide line is identical with that drawn in fig 1.7.2.1. The dispersion is considerable owing to the varying conditions of production and destruction represented in the material. The distribution of the samples from a core in this type of diagram appears in many cases to give information with regard to some of the environmental conditions.

The deviations in the relationship between the concentration of entire foraminifera and the concentration of calcium carbonate appear to be of diagnostic value with regard to the environment conditions, and this relationship has therefore been studied separately in all cores in carbonate facies (§ 2.38.7—2.62.7). Abnormally high concentrations of entire foraminifera in marl oozes, as in the Galapagos area, indicate a high total rate of accumulation, preventing a long exposure of the tests to the sea water, a great resistivity of the tests against crushing and dissolution and small dimensions of the specimens, making the number of tests per gram calcium carbonate great. All these factors appear to be of importance in cores 38—40.

Abnormally low concentrations in carbonate rich eupelagic chalk oozes appear to be a good indicator of abundance of coccoliths. Coccolithic chalk oozes thus form the protuberances from the lower, right side of the distribution body in fig. 1.7.2.1 as well as the isolated sample group in the lower, right corner of this graph. Regression slopes, lower than the eupelagic average and approaching 1, indicate that the comminution of the tests by dissolution has lost much of its influence and thus probably that the bottom water was relatively warm. These conditions are found in the calcareous Tertiary core 53 (§ 2.53.7).

Extensive scattering is believed to indicate great changes in the environment conditions,

poorly defined conditions, or extensive postdepositional dissolution as in core 41 (§ 2.41.7).

1.7.3 Variations in composition of the planktonic fauna.

The first worker to make systematic use of the distribution of foraminifera in pelagic sediment cores for a paleoecological interpretation of the sequences was SCHOTT (1935), who founded his work on a comparison between the distribution of living planktonic assemblages and the fossil distribution in the bottom deposits. SCHOTT demonstrated that an extensive change of the percentage composition of the thanatocoenosis is brought about by differential dissolution of the tests. Although several factors have been recognized as causing or possibly causing discrepancies between the composition of the living assemblages and the thanatocoenosis in the case of planktonic foraminifera (cf. e. g. PHLEGER 1951, p. 68), the extensive diagenetical changes of the dead assemblages, demonstrated by SCHOTT, do not appear to be generally realized. This is understandable as the results of corrosion are not very obvious from studies of foraminifera at moderate enlargement and in reflected light (see § 1.12.6). From SCHOTT's results it is evident that the changes in faunal composition recorded in pelagic sequences are dependent both on changes in the composition of the living assemblages and on changes in the conditions of dissolution and fragmentation of the tests. SCHOTT found e. g. *Globigerina sacculifera* and *Orbulina universa* to be very sensitive to corrosion and *Globorotalia tumida* to be more resistant than *G. menardii*. The present results further indicate that of the Equatorial Pacific planktonic species *Globigerina rubra*, *Globigerina inflata* and *Globigerina cf. bulloides* (the latter here included in the group *Globigerina spp*, cf. ch. 4.9) belong to the comparatively resistant forms, whereas *Globorotalia menardii* belongs to the group which is relatively sensitive to crushing and corrosion. Recrystallized specimens appear not to be as easily attacked as those which have retained their original structure. Benthonic forms generally appear to be much more resistant than planktonic forms.

With these conditions in mind it appeared necessary to use great care in the paleoecological interpretation of the faunal composition recorded, and before interpretations were suggested an attempt was made to check the significance of the percentage changes by correlation with other sediment properties known to reflect environmental changes, such as rate of biogenous accumulation or calcium carbonate content.

.1 *Globorotalia and Globigerina.* The most significant stratigraphical change in faunal composition found by SCHOTT in the Equatorial Atlantic Ocean sediments was the alternating dominance of *Globigerina* species on the one hand and *Globorotalia* species (mainly *Globorotalia menardii* and *G. tumida*) on the other. These variations formed the basis of SCHOTT's paleoecological interpretation of the sequences investigated. Comparatively small use was made of other faunal elements than the *Globorotalia* species as the comparison between the biocoenosis and the thanatocoenosis in its postdepositional state had demonstrated that the distribution on the deep sea bottom mostly reflected to a higher degree the changing conditions of dissolution and disintegration than the original composition of the living assemblages. SCHOTT recognized, too, that also the distribution of *Globorotalia* in the sediments was secondarily influenced, but the extensive percentage changes recorded were believed to justify the paleoecological conclusions drawn.

The present results indicate that when a planktonic assemblage is exposed to dissolution and mechanical disintegration on the deep sea bottom, the outer shell of *Orbulina universa* is quickly destroyed which is also confirmed by SCHOTT's results. The *Globorotalia* species

occupy an intermediate position. SCHOTT's observations indicate that *G. menardii* is more readily destroyed than *G. tumida*. As these two were not separated (cf. ch. 4.9) in the present investigation, this effect could not be checked. The least affected planktonic forms appear to be thick-walled, small or compact foraminifera, mostly *Globigerina* species, (cf. § 2.45.7 and 2.53.7). The Last Glacial stage, of the Equatorial Atlantic Pleistocene series, found by SCHOTT to have a strongly reduced percentage of *Globorotalia*, is simultaneously poor in calcium carbonate, probably due to the increased dissolution caused by increased inflow of cold deep and bottom water during the Ice Ages. According to the opinion of the present author, based on corrosion studies in the Equatorial Pacific, the extensive percentage decrease of *Globorotalia* recorded in the glacial stages of Equatorial Atlantic sequences might be explained as caused by selective disintegration and dissolution. If a check of this hypothesis proves it to be true, it would not interfere with the correctness of SCHOTT's stratigraphical interpretation. Only the explanation would be altered; the changes recorded would not mainly (but certainly partly) be due to the changed ecological conditions at the surface of the ocean but to the changed conditions of dissolution and reworking at the ocean bottom.

In the Equatorial carbonate facies of the East Pacific Ocean the changes of carbonate content in the Upper Pleistocene are contrary to those found in parts of the Equatorial Atlantic Ocean; glacial strata being rich and interglacial strata poor in carbonate. This difference is due (ch. 1.1) to the fact that the rate of calcium carbonate production in the east part of the Equatorial Current system in the Pacific was during the Ice Ages increased to such an extent that it greatly surpassed the reinforced rate of dissolution, whereas in the Atlantic the distribution of surface currents does not appear to make possible a corresponding effect. Further, in the Equatorial Atlantic the Antarctic bottom and deep water appears to exert still greater influence on the carbonate content of the bottom deposit than in the Equatorial Pacific (cf. ch. 1.1).

The distribution of *Globorotalia menardii* + *tumida* in the East Pacific sequences demonstrates that statistically there is an inverse relationship between the fraction of *Globorotalia* in the planktonic fossil assemblages and the concentration of foraminifera in the sediment, i. e. the glacial strata are low in *Globorotalia menardii* and *tumida*, which is in good agreement with SCHOTT's view on the temperature requirements of the *Globorotalia* species in question. This view has later been confirmed by other workers, e. g. PHLEGER (references in PHLEGER, 1951) and OVEY (OVEY, 1948, WISEMAN and OVEY, 1950).

The relationship between concentration of planktonic foraminifera in the sediment and faunal percentage of *Globorotalia* in the East Pacific Eupelagic sediments is shown in fig. 1.7.3.1 and the stratigraphical percentage distribution of *Globorotalia* is shown in pl. 2.38—2.62 and fig. 1.7.3.2. From fig. 1.7.3.1 is seen that there is a significant relationship between the two properties shown, although the dispersion is great. The distribution in each core is shown separately in fig. 2.38.7.2—2.62.7.2. Two main factors are believed to contribute to the dispersion of the relationship. Firstly this is counteracted by dissolution and fragmentation, which tends to decrease the percentage of *Globorotalia* and which is for reasons quoted in ch. 1.1 most active in the minima of calcium carbonate and foraminiferal concentrations. This effect is believed to be illustrated by the distributions e. g. in core 45 and 46, where the low concentrations of foraminifera are connected to very low rates of calcium carbonate accumulation in the Pleistocene (fig. 2.45.7.3 and 2.46.7.3).

Secondly the percentage of *Globorotalia* in

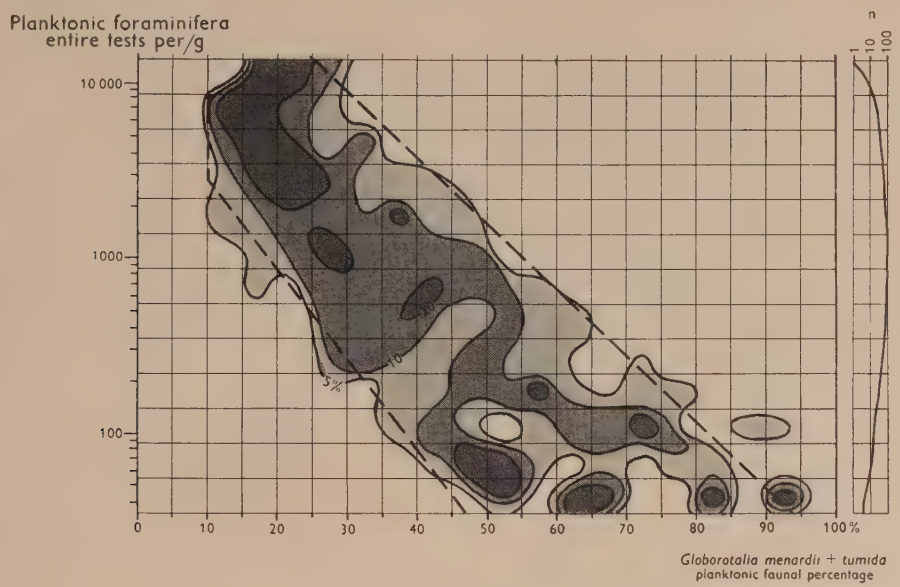

Fig. 1.7.3.1. Relation between concentration of planktonic foraminifera and percentage of *Globorotalia menardii + tumida* in the fossil planktonic foraminiferal assemblages of the East Eupelagic area. The guide lines drawn in the graph are the approximate borders of the field within which 90 % of all samples are located High percentages of *Globorotalia* are believed to indicate warm surface water and these conditions are obviously connected with low concentrations of planktonic foraminifera (low productivity), whereas the low percentage of *Globorotalia* in strata rich in planktonic tests, and therefore high in calcium carbonate, indicate that these were deposited during ages with a lowered surface temperature of the ocean. The dispersion of the relationship is believed to be caused mainly by the lack of proportionality between the rate of production and concentration of entire planktonic tests and by the differential dissolution of the foraminiferal tests. This latter effect tends to decrease the high percentages of *Globorotalia*.

the biocoenosis is believed to be directly dependent on the water temperature of the surface layer and thus, in the present area, on the rate of upwelling. The concentration of foraminifera is related to the rate of production and through this also to the rate of upwelling. The concentration of foraminifera in eupelagic deposits is, however, influenced also by the total rate of destruction of tests. There is thus no immediate relationship between the relative composition of the foraminiferal plankton fauna and the concentration of tests found in the sediment, but both are strongly influenced by the same factor, viz. the rate of upwelling. Variations in the rate of destruction of tests are believed largely to contribute to the dispersion found.

The correlation between concentration of foraminifera and percentage of *Globorotalia* can for reasons quoted above not have been created by secondary effects, as these tend to cause a distribution inverse to the one found. The distribution found is therefore looked upon as a reliable confirmation of the fact that an increased concentration of foraminifera and of calcium carbonate in the East Equatorial carbonate facies indicates a lowered temperature of the surface water (reinforced upwelling). This is also shown by the present regional distribution of calcium carbonate (§ 1.1.3). The great dispersion makes it impossible to use the stratigraphical distribution of *Globorotalia* as a decisive indicator of the environmental conditions. Judged together with the lithological properties of the sediment and with proper regard taken to the possibilities of selective destruction, the distribution of *Globorotalia* might, however, be used for stratigraphical purposes.

The stratigraphical distribution of *Globorotalia* in the East Eupelagic carbonate section is shown in fig. 1.7.3.2. Percentages lower

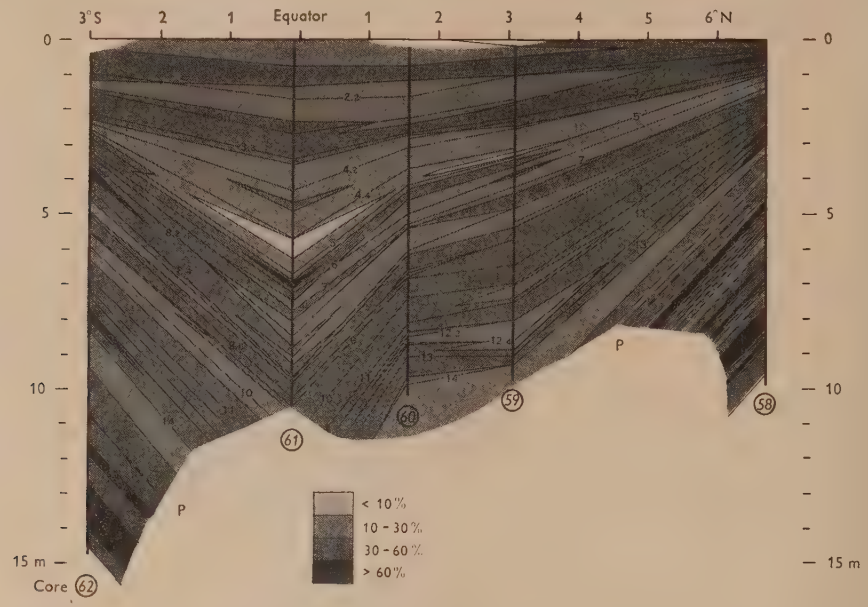

Fig. 1.7.3.2. Planktonic faunal percentage of *Globorotalia menardii + tumida* in the East Eupelagic carbonate area. Vertical lines correspond to sediment cores. Core numbers are inserted below the diagram. The stratigraphical position of stage and substage maxima and minima are indicated by labelled lines. P = Pliocene-Pleistocene boundary.

than 10 % are restricted mainly to the area below the Equatorial Divergence (core 61), where the regional rate of upwelling of cold deep water attains its maximum, and to age 4, when the rate of upwelling reached the highest values recorded. Very low percentage values are further characteristic of the Galapagos area (core 38—40) where the rate of upwelling is known to be very high and the temperature of the surface water attains the lowest values found in the tropical region of the oceans (G. SCHOTT, 1935). A high frequency of values above 60 % of *Globorotalia* is found in the Pliocene sediments, forming the lower parts of the cores 62 and 58. Further, low percentages of *Globorotalia*, indicating low surface temperatures, are more frequent in the Upper Pleistocene stages, believed to correspond to the last Ice Ages (stages 2, 4 and 6), than in the corresponding Lower Pleistocene even-number stages. This confirms that the equatorial circulation during the last three or four Ice Ages was more intensified than during the preceding ones. A subordinate *Globorotalia*-maximum in the upper part of stage 2 might indicate a Late Glacial temporary lowering of the rate of circulation.

As a result of the variations in percentage of *Globorotalia*, the percentage of *Globigerina* is subject to complementary changes and an inverse relationship to that found between content of foraminifera and percentage of *Globorotalia*, is developed between content of foraminifera and percentage of *Globigerina* (fig. 1.7.3.3). This genus was subdivided according to ch. 4.9, but as no possibilities were found to check whether the variations in the subordinate taxonomic groups reflect variations in the living assemblages or in the conditions of dissolution and fragmentation, they could not be used for interpretation purposes. It is hoped that further quantitative experiments will reveal the differences in solubility and tendency to fragmentation between different species.

.2 *Orbulina universa* d'Orbigny. W. SCHOTT (o. c.) demonstrated that the tests of *Orbulina universa* are easily destroyed and that the proportion present in the pelagic sediments does in no way correspond to the proportion

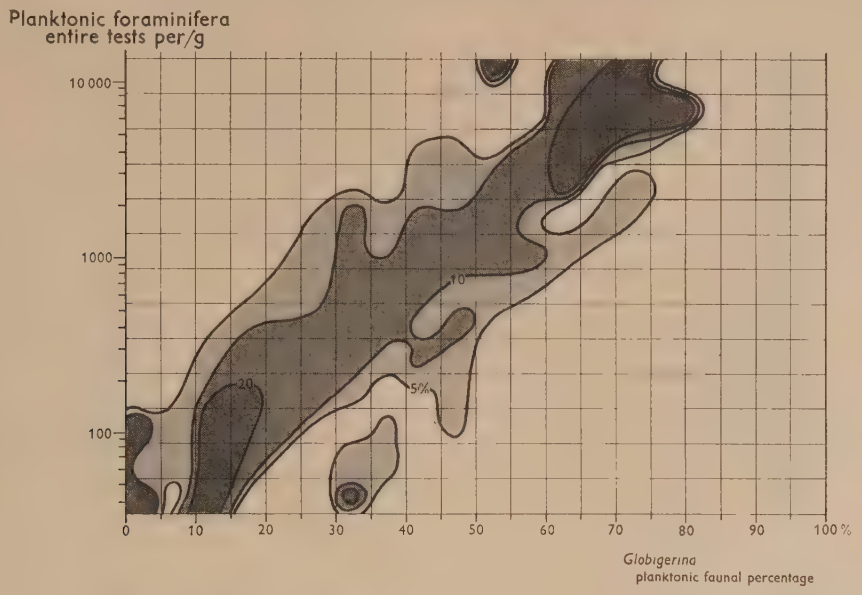

Fig. 1.7.3.3. Relation between concentration of planktonic foraminifera in the East Eupelagic area and faunal percentage of specimens belonging to the genus *Globigerina*. The comparatively low dispersion indicates that all quantitatively important *Globigerina* species (mainly *Globigerina spp.* cf. *G. bulloides*) react much in the same way to the ecological changes influencing the concentration of planktonic tests. The distribution of *Globorotalia* (fig. 1.7.3.1) indicates that a high concentration of planktonic tests corresponds to low surface temperatures, and dominance of the genus *Globigerina* is thus found in connection with cool surface water. It should be noted that this distribution of the *Globigerina* species is not used as a proof of cool water conditions.

in the living assemblages. SCHOTT's observations are confirmed by the present material. As is seen from fig. 1.7.3.4, the percentage of outer shells of *Orbulina universa* does not exceed 3 % in the East Eupelagic sediments and the correlation between the species percentage and the concentration of planktonic foraminifera is low. The slightly increased frequencies in low-moderate foraminiferal concentrations correspond to samples from the Pliocene parts of cores 58 and 62 and indicate that the rate of destruction of tests was lower in the Upper Pliocene than in the Pleistocene in spite of the fact that the total rate of deposition was low and the tests thus exposed to the bottom water during a comparatively long time. This is probably explained by the relatively high temperature of the Tertiary bottom water.

Comparatively high percentages (5—10 %) are found in the Galapagos area (cores 38—40) where the total rate of deposition is high and the tests thus rapidly protected. It is not impossible that the ecological conditions (cold surface water, high productivity) in this area also contribute to the increased percentage of *Orbulina universa*. It should be mentioned in this connection that *Orbulina universa* belongs to the species which are absent or lower in frequency in the »Lower fauna» (cold water) described by PHLEGER (1951) from the Gulf of Mexico. This indicates either that *Orbulina universa* is restricted to warm water or that at least the outer shells are dissolved from the strata containing the »Lower fauna» in the Gulf of Mexico. The comparatively high frequency of *Orbulina universa* in the Galapagos area makes the latter alternative most probable. It should, however, be pointed out in this connection that the effects of selective destruction on fossil assemblages might be expected to be lower in the shelf environment, which was the object of PHLEGER's investigation, than in the pelagic environment, where the rate of deposition is low

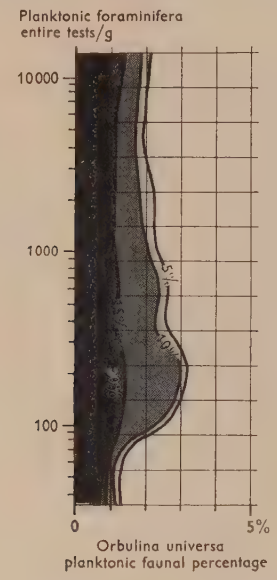

Fig. 1.7.3.4. Relation between concentration of planktonic foraminifera and faunal percentage of outer shells of *Orbulina universa* in the East Eupelagic area. The percentage found in the sediment is very low and appears practically completely to be determined by secondary destruction of the *Orbulina* tests. A slightly increased percentage is found in the Upper Pliocene samples from core 58 and 62, forming the bulge of the distribution body in low-intermediate concentrations of planktonic tests. This is certainly not due to ecological conditions, as high percentages are found in the Galapagos cold water area in such environments where the tests are rapidly buried, but most probably to the low aggressiveness of the Tertiary bottom water.

waters (PHLEGER 1951), it is, however, conand the deposited tests are left unprotected at least during several decades. Occasional high percentages of *Orbulina* (up to 14 %) are found e. g. in cores 41 and 47, which are believed to contain abnormally rapidly deposited material. From these facts it is concluded that the distribution of outer shells of *Orbulina universa* in equatorial pelagic sediments has no or doubtful ecological significance but that this species is a sensitive indicator of the conditions of dissolution at the bottom. Dissolution during settling is believed to play a subordinate role as the settling velocity is high (W. SCHOTT, o. c., KUENEN, o. c.) and as specimens which are only moderately corroded are found in rapidly deposited deep sea sediments. Statistically significant percentages higher than 2 in eupelagic deposits indicate a markedly decreased aggressiveness of the bottom water as compared with Late Pleistocene conditions.

.3 *Pulleniatina obliquiloculata* (Parker and Jones). The factors determining the distribution of *Pulleniatina obliquiloculata* appear to be complicated. This species belongs to those which are absent or lower in frequency in PHLEGER's (o. c.) »Lower fauna» (cold water) of the Gulf of Mexico. This is in agreement with the fact that the percentage is very low (< 1 %) in the Galapagos cold water area (cores 38—40). As the conditions here favour the preservation of calcareous structures very sensitive to dissolution such as the outer shell of *Orbulina universa*, the absence of *Pulleniatina* from the Galapagos cores and from the »Lower fauna» in the Gulf of Mexico is not believed to be an effect of differential dissolution. In cores 45 and 46 (pl. 2.45 and 2.46) the stratigraphical variation of *Pulleniatina* resembles that of *Globorotalia* except that the percentage is markedly decreased in the strata where the percentage of *Globorotalia* attains very high values. This indicates either that *Pulleniatina obliquiloculata* is favoured by moderate water temperatures or conditions connected to moderate temperatures, or that secondary destruction balances and surpasses the ecologically determined percentage increase, when the total rate of accumulation is greatly reduced. The former alternative is favoured by the fact that the percentage of *Pulleniatina* is low in the Pliocene strata represented by the lower parts of cores 58 and 62 and which were deposited when the surface water temperature was high, the rate of upwelling low, and the rate of dissolution of carbonate at the bottom so low that the percentage of preserved *Orbulina* tests was markedly higher than in the Pleistocene. In the Pleistocene of core 58, *Pulleniatina* attains dominance in several strata, mostly connected to an increased rate of production. In the Pleistocene of other calcareous eupelagic cores (59—62) *Pulleniatina* does

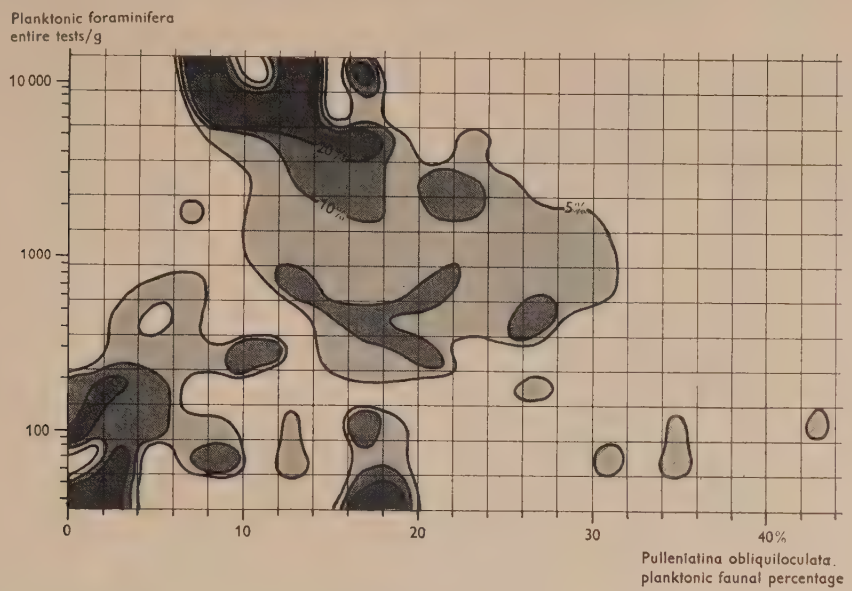

Fig. 1.7.3.5. Relation between concentration of planktonic foraminifera and faunal percentage of *Pulleniatina obliquiloculata*. The percentage of this species appears to be negatively affected by conditions connected with very high and very low concentrations of foraminifera but to be independent when the concentration of entire planktonic tests is intermediate.

not appear to be considerably influenced by the extensive changes in surface water temperature, except in substage 4.2 of core 61 below the Equatorial Divergence where the percentage is strongly lowered. This substage appears to represent the most extensive rate of upwelling which has ever occurred in the East Eupelagic section and thus an extensively lowered surface temperature.

The composite distribution of *Pulleniatina obliquiloculata* is illustrated by fig. 1.7.3.5, which shows the relation to the concentration of foraminifera. The percentage appears to be depressed at very high concentrations of foraminifera (maximum circulation) and at very low concentrations (Pliocene conditions) and to be independent of the concentration of foraminifera (rate of production and circulation) when this is intermediate. As was mentioned above it is regarded as fairly certain that the low percentages connected to low concentrations of foraminifera are not caused by differential dissolution in this case.

.4 Sphaeroidina bulloides (d'Orbigny) *and Sphaeroidinella dehiscens* (Parker and Jones). *Sphaeroidina bulloides*[1]) constitutes the main part of the always small percentages of the group *Sphaeroidina* + *Sphaeroidinella* which are found in the Pleistocene series of the East Pacific. Regular and quantitatively important occurrences of *Sphaeroidinella dehiscens* are limited to the Upper Pliocene strata represented by the lower parts of cores 58 and 62. In the Upper Pliocene of the former core, strata are found with such a high percentage of this species, that the deposit has to be classified as sphaeroidinella marl ooze. The transition from Upper Pliocene to Lower Pleistocene is characterized by a marked drop in the percentage of this species. This distribution is also reflected in the relationship: species percentage — concentration of foraminifera (fig. 1.7.3.6). *A priori* it is not known whether this typical distribution of *Sphaeroidinella dehiscens* is determined by the ecological conditions or by the sensitivity of the test to dissolution. From the scarcity of this species in present temperate

[1]) *Sphaeroidina bulloides* has been considered a benthonic species by some authors. Its inclusion has, however, little effect on the planktonic group as a whole because of its relative rarity.

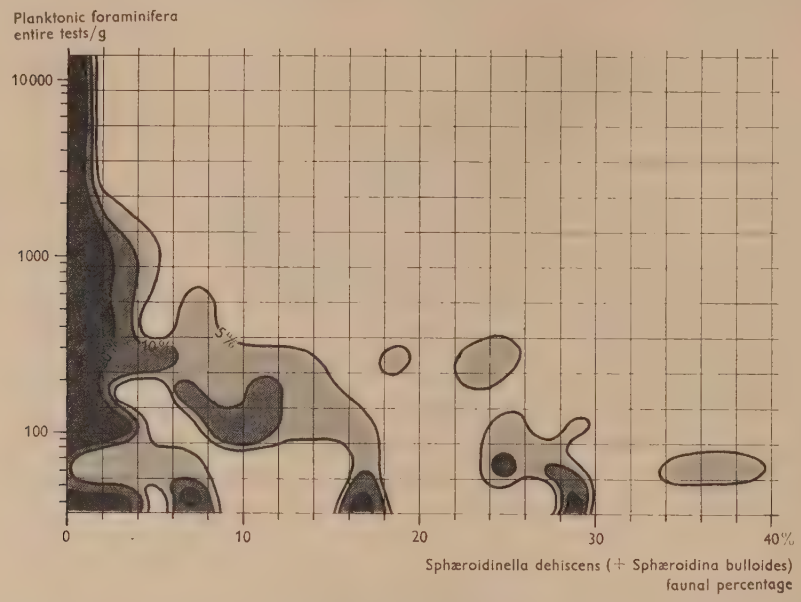

Fig. 1.7.3.6. Relation between concentration of planktonic foraminifera and faunal percentage of *Sphaeroidinella dehiscens* + subordinate amounts of *Sphaeroidina bulloides*. Very low percentages occur in strata rich in pelagic foraminifera (with a high rate of production and cool surface water). In intermediate and low concentrations both high and low percentages occur. These low percentages are found in the Pleistocene low-circulation ages (odd number stages), whereas high concentrations of *Sphaeroidinella dehiscens* are entirely restricted to the Upper Pliocene strata represented by the lower parts of cores 58 and 62. This distribution is most probably not an evolutionary effect but is believed to be caused by the Pliocene ecological conditions (high surface water temperature, relatively high deep water temperature, low rate of upwelling). The possibility cannot be excluded that differential dissolution contributes to the lowering of the Pleistocene percentages, but the present distribution of *Sphaeroidinella dehiscens* in living plankton indicates that the ecological factor is of primary importance in this case.

cluded that the ecological factor is of decisive importance in this case. Thus in the present East Equatorial Pacific carbonate area, *Sphaeroidinella dehiscens* appears to be an indicator of ecological conditions connected with a very low rate of upwelling.

1.7.4 Concentration of benthonic foraminifera.

The aims of the present investigation include the study of the quantitative relationships of bathyal benthonic foraminifera, treated as one single group. Taxonomical relationships are not dealt with in this connection, but will be treated separately by Brotzen.

Observations of the varying concentration of benthonic foraminifera in Pacific sediments were made by Revelle (o. c.), who pointed out that a high percentage of benthos is related to a low calcium carbonate content, a high percentage of broken tests of pelagic foraminifera and a high content of organic matter. The latter conclusion was drawn from the content of nitrogen which is here shown to be unrepresentative of the content of organic matter but to reflect the percentage of clay (ch. 1.4). The former observations, however, are confirmed by the present investigation.

The relationship between the concentration of entire tests of planktonic foraminifera and the concentration of benthonic tests in the East Eupelagic sediments is shown in fig. 1.7.4.1. From this graph is seen that there is a linear logarithmic relationship between the two properties, viz. $\log p = 3 \cdot \log b - 3.6$ or $p = b^3/4\,000$ or $b = 16\sqrt[3]{p}$ if p is the concentration of entire planktonic tests and b the concentration of benthonic tests. Thus, when the concentration of entire planktonic

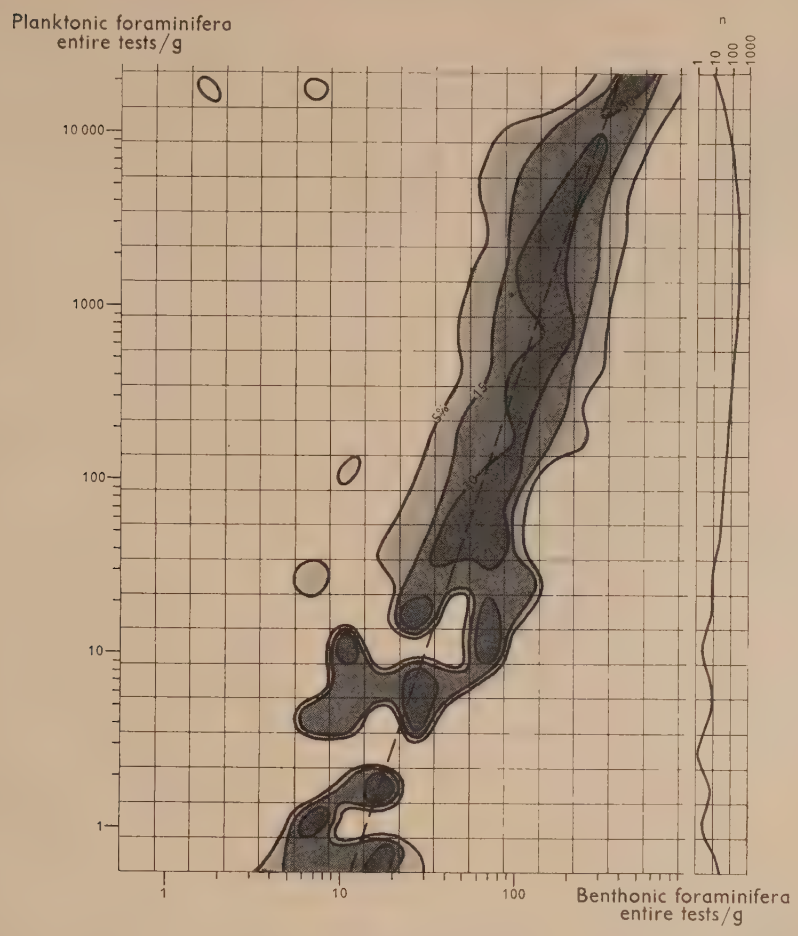

Fig. 1.7.4.1. Relation between concentration of entire planktonic tests and of benthonic tests. The graph illustrates the observation made by REVELLE in regionally different samples, that low concentrations of calcium carbonate and of entire planktonic foraminiferal tests occur together with comparatively high concentrations of benthonic foraminiferal tests. The dashed line represents the function $b = 16\sqrt[3]{p}$; p = conc. entire planktonic tests, b = conc. entire benthonic tests.

tests increases, the number of benthonic tests increases too but in proportion to the third root of the former variable. When 63 entire planktonic specimens occur in a 1 g sample the benthonic tests thus amount to 100 % of this value but in the case of a concentration of 10 000 entire planktonic tests per gram sediment the amount of benthonic tests is only 3.4 % of the pelagic number. This is a quantitative illustration of the conditions observed by REVELLE (o. c.). At the interpretation of this relationship it should be noted that much of the increase in number of entire pelagic tests is not due to an increased rate of accumulation of tests but to the fact that the rate of fragmentation of the tests decreases when the total rate of accumulation increases (§ 1.7.1). The benthonic species on the other hand appear to be very resistant to dissolution and mechanical disintegration, probably because of the compact microstructure of their tests, which are adapted to the aggressive bathyal environment. Fragments of benthonic species are thus relatively rarely found in the sediments here in question, and it is believed that the rate of accumulation of entire benthonic tests is approximately identical with the rate of production of benthonic tests, at least when the total rate of accumulation is moderate or high.

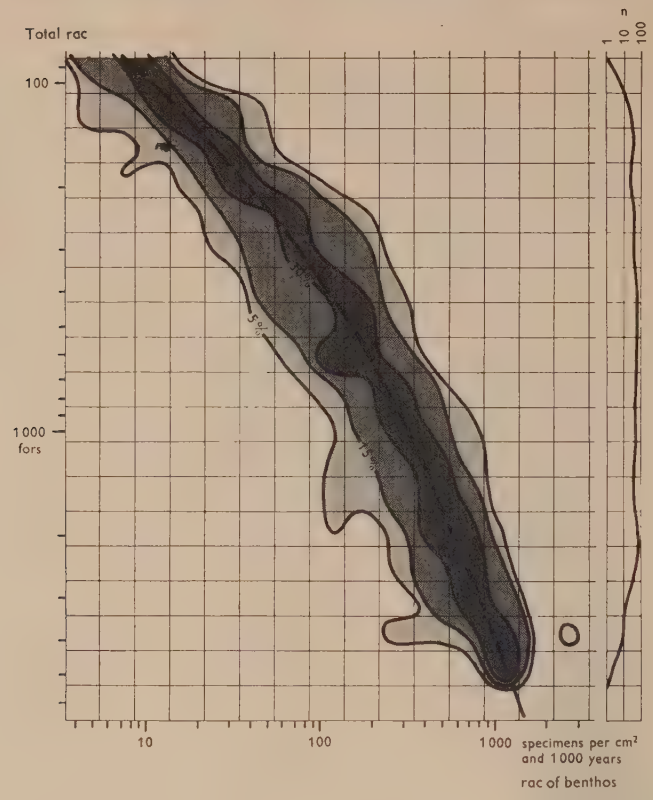

Fig. 1.7.4.2. Relation between total rate of accumulation and rate of accumulation of benthonic foraminifera in the East Eupelagic carbonate area. The protuberances from the distribution body to the left are caused by samples rich in coccoliths. The dashed line is the estimated regression line corresponding to the function f_1 (*total rac*).

The relation between total rac and rac of benthos is shown in fig 1.7.4.2. From this is seen that a small change in the total rac has a greater effect upon the rac of benthos when the total rac is low than when it is high. This is due to the fact that when the total rac is low, the biogenous rac (= *rac* $CaCO_3$ + *rac biogenous silica*) approaches zero (biogenous rac = 0 for total rac = 74 fors). Thus a relatively small change of a low total rac is corresponded by a relatively great change in the biogenous rac. This latter property is probably of more direct importance for the production of benthos than the total rac. The function *rac benthos* = f_1 (*total rac*), represented by the dashed regression line of fig 1.7.4.2 (estimated), has therefore graphically been transformed to *rac benthos* = f_2 (*biogenous rac*) and the latter relationship is shown in fig 1.7.4.3. From this it is seen that the rac of benthos is only moderately affected by changes in the biogenous rac when this is very low. This is believed to depend on the fact that at a very low biogenous rac (= *rac* $CaCO_3$ + *rac biogenous silica*), this property is no longer a good measure of the rate of deposition of organic detritus, which serves as the food of the benthonic foraminifera. The discrepancies in the proportionality between biogenous rac and rate of deposition of organic detritus are caused by the rate of dissolution of $CaCO_3$ which approaches and attains 100 % of the rac of $CaCO_3$ when the biogenous rac is low (cf ch 1.1). If there were no dissolution of calcium carbonate, the approximate relationship *rac benthos* = f_3 (*biogenous rac*), indicated by the dashed line in fig 1.7.4.3 is assumed to have existed. The numerical ordinate difference between the two functions e. g. the numerical difference $y_3 - y_2$ in fig. 1.7.4.3 expresses the rate of dissolution of calcium carbonate.

With intermediate values of biogenous rac the dissolution of carbonate is no more of great relative importance, and f_2 (*biogenous rac*) approaches k (*biogenous rac*), where $k \approx 3$. A change of the biogenous rac from 100 to 1 000 fors thus causes an increase of the rac of benthos from 32 to 330, i. e. the accumulation ($\approx$ production) of benthos is practically in direct proportion to the accumulation of biogenous matter which in its turn is probably in direct proportion to the supply of edible organic detritus at the sea bottom.

When the biogenous rac is very high, the rate of increase of rac of benthos again becomes smaller, so that an increase of the biogenous rac 3.9 times (from 1 000 to 3 900 fors) causes an increase of the rac of benthos of only 3.1

times (from 331 to 1 000 specimens per cm² in 1 000 years). This is believed to indicate that at very high rates of biogenous accumulation, the supply of organic detritus at the bottom loses some of its importance as a limiting factor of the production of benthonic foraminifera. As high rates of biogenous accumulation occur together with increased aggressiveness of the bottom water it might be suggested that this latter property exerts a limiting influence on the production of calcareous benthos in the bathyal environment.

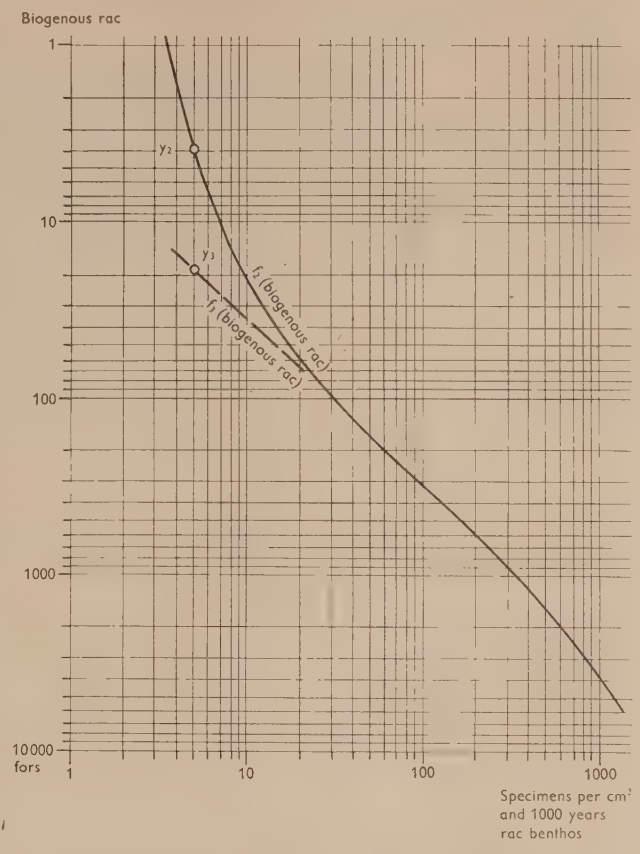

Fig. 1.7.4.3. Relation f_2 (*biogenous rac*) between rate of biogenous accumulation and rate of accumulation of benthonic foraminifera (full line). This function has been graphically transformed from f_1 (*total rac*) in fig. 1.7.4.2, using the relationship; *biogenous rac* = *total rac* — 74 fors (§ 1.2.10). The dashed line corresponds approximately to the hypothetical function f_3 (*biogenous rac*) = f_3 (*biogenous rate of production*), which would be valid if there were no dissolution of calcium carbonate.

1.8 Radiolaria

1.8.1 Scope and limitation of the study.

The investigation of the radiolaria comprised partly a study of the stratigraphical distribution of different taxonomic groups, partly an investigation of the total concentration in the sediment of radiolaria > 150 μ. The present chapter deals with the results of the latter investigation.

Owing to the poorly defined size of many types of radiolaria and to technical difficulties at fractioning the skeletal remains (ch. 4.9), the error inherent in the concentration values is great in comparison with the error of the foraminiferal concentrations and the scattering which is seen in pl. 2.58—2.62, col. Radiolaria, is to a great extent due to the comparatively low accuracy of the measurement.

1.8.2 Concentration of radiolaria in the East Pacific Ridge sediments.

Except in cores 38 and 39, where the siliceous structures are well preserved, the radiolaria in the East Pacific Ridge sediments are nearly always found to be slightly or strongly corroded or almost completely peptized. This effect is further treated in ch. 1.12. Consequently the distribution of radiolaria in the East Pacific Ridge area is of subordinate interest from a stratigraphical point of view, except in the Galapagos area (cores 38—39). In this area the order of magnitude of the concentration of radiolaria is the same as in core 58 in the East Eupelagic area and the rate of accumulation of radiolaria is of the same order of magnitude as in core 61. The distribution in core 39 (pl. 2.39, col. Radiolaria) indicates that the rate of accumulation of radiolaria was strongly increased in ages 4 and 2 and higher in the former than in the latter age.

The secondarily altered distributions in the other cores from the East Pacific Ridge are

shown in pl. 2.40—2.48 and are discussed in § 2.40.8—2.48.8.

1.8.3 Distribution of radiolaria in the North Equatorial clay area.

Secondary peptization of siliceous structures is far-reaching also in the North Equatorial clay area, and in many cases it is impossible to estimate the original concentrations, especially when the peptization is complete and no skeletal remains of radiolaria are found. In many cases the concentration is comparatively high in the top strata and decreases with increasing depth in the sediment, which is believed to indicate slow, posthume peptization, as the frequency of traces of corrosion increases with depth. When high contents return in old strata, as is the case e. g. in cores 54 and 57, it is not known whether this indicates a high rate of deposition of radiolaria in these strata or an environment favouring preservation of the siliceous structures. A qualitative estimation based upon the amount of visible remains of radiolaria, the concentration and state of preservation of more resistant siliceous remains (sponge spicules), and the apparent amount of colloidal silica, indicates that cores 50, 51, and 52 furthest to the north, and the calcareous Tertiary core 53, were never very rich in radiolaria, whereas cores 55, 56, and 57 from the region bordering the Equatorial carbonate area, were probably once rich and still are comparatively rich in siliceous skeletal remains. Core 48 from the same facies but situated further to the east, was probably originally rich in siliceous remains, but is now poor, apparently due to posthume peptization (cf. ch. 1.12). The reason for the increased tendency to peptization of the siliceous structures in the East Pacific Ridge sediments in comparison with the East Eupelagic area is not known. Extensive measurements of the pH did not indicate that the sediment is exceptionally alkaline in the former area.

1.8.4 Distribution of radiolaria in the East Eupelagic carbonate area.

Corrosion of the siliceous remains is of much less importance in the East Eupelagic area than in the East Pacific Ridge sediments and in the North Clay. The diatoms, which are still more sensitive to peptization than the radiolaria, are generally in a good state of preservation. Only in core 58, where the average rate of accumulation is low (0.4 cm/1 000 years in the Pleistocene) the corrosion of diatoms and radiolaria becomes obvious.

The rate of accumulation of radiolaria in the East Eupelagic carbonate facies is shown in fig. 1.8.4. From this is seen that there is good agreement between the main features of the distribution of rac of radiolaria and of biogenous silica (fig. 1.3), the highest values being found in the Pleistocene strata of increased circulation and production (even number stages) and below the Equatorial Divergence (core 61). Small differences in the rac of biogenous silica and of radiolaria might be explained by the error involved in the determination of the number of radiolaria (§ 1.8.1). Other features of the distributions, however, indicate real differences between these two properties. Thus the amplitudes of the variations in rac of radiolaria appear to be smaller than in the rac of biogenous silica, and also the regional differences, e. g. between cores 61 and 60, are less accentuated in the case of the rac of radiolaria. This indicates that the radiolaria, which are known to inhabit the entire water column, are influenced less by changes in the circulation of the surface currents than is the concentration of biogenous silica, which includes the diatoms. These are restricted to the euphotic layer of the ocean and are known to be very sensitive to the rate of upwelling (ch. 1.9).

The comparatively low Pliocene rac of radiolaria found in core 58, is believed, at least partly, to depend on a high rate of peptization connected to the low total rate of accumulation.

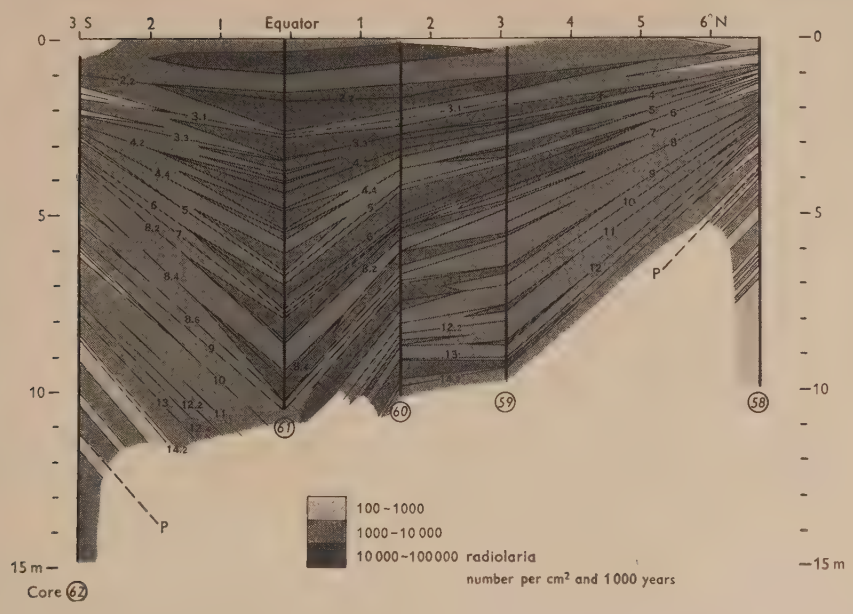

Fig. 1.8.4. Rate of accumulation of radiolaria > 150 μ in the East Eupelagic carbonate section (cf fig. 1.0). Vertical lines correspond to sediment cores. Core numbers are indicated below the diagram and stage and substage centers within this. P = Pliocene — Pleistocene boundary. The scales on both sides of the graph indicate depth in the sediment. Further details of the construction of this type of diagram are given in § 1.0.3.

1.9 Size distribution of Coscinodiscus nodulifer

1.9.1 Observations leading to the study.

In connection with the quantitative microscopical analysis of the grain size fractions > 150 μ, it was observed that a large centric diatom occurred in certain strata. This occurrence appeared remarkable, as in normal cases no diatoms are retained on the 150 μ sieve. As high frequencies of the giant form were found to be restricted to definite time-rock units, a systematic and quantitative study of this species was considered to be of stratigraphical interest. The identification, which was kindly carried out by KOLBE (vol. V, part 5), demonstrated that the species in question was identical with *Coscinodiscus nodulifer* A. Schm. KOLBE's investigation showed further that this diatom displays here a very great range in size viz. from 13 to appr. 200 μ.

Steps were next taken to determine the size frequency distribution of this *Coscinodiscus* species as a function of depth in the sediment and thus finally of time. The size determinations were carried out by microscopical measurement of the diameter of 300—400 specimens in each sample with a size class interval of 10 μ. Parallel investigations were carried out on several samples from the same level in order to test the methodical deviations and sampling errors (fig. 1.9.1.1.—1.9.1.2). All preparations as well as the microscopical measurements were carried out by Kolbe, during the first part of the investigation. Later on, parts of the measurement work were taken over by a team (§ 4.9.1) trained and supervised by Kolbe. Appr. 340 samples from the East Pacific have been investigated, corresponding to appr. 120 000 measurements.

1.9.2 Results.

The different types of size frequency distribution obtained have been exemplified in fig. 1.9.2.1 and 1.9.2.3. The type represented by the samples 59—443, 60—80 and 61—80

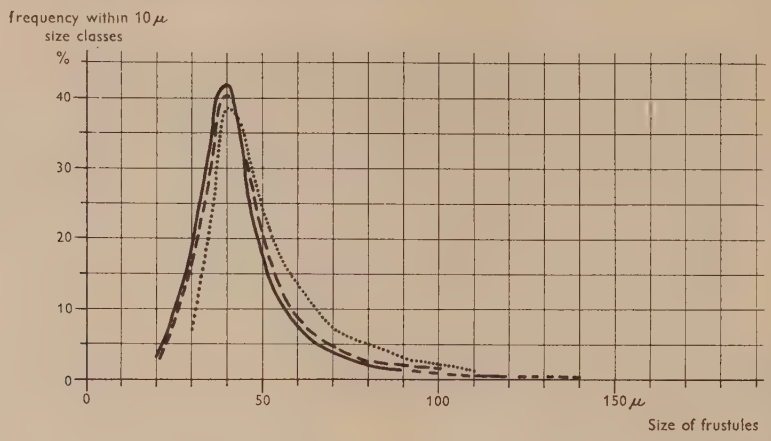

Fig. 1.9.1.1. Size-frequency distribution of *Coscinodiscus nodulifer* in two parallel samples of the sample 59—40. Full line; sample *a*, unwashed. Dashed line; sample *b*, unwashed. Dotted line; sample *b*, washed (normal analytical pretreatment; cf. § 4.9.2).

shows a marked maximum in the size interval 30—50 μ. The tendency toward small subordinate maxima in large sizes is indicated also in these samples. Populations of the type 60—80 might at first sight appear to be homogenous and the frequencies to be normally distributed with regard to the logarithm of the size if the distribution above 110 μ is neglected. Plotting the values in a probability graph (normal distribution) (fig. 1.9.2.2), however, shows that the distribution of the values below 100 μ is bimodal, one component consisting of frustules appr. 50—90 μ and the other one comprising the specimens smaller than appr. 40 μ. The former group might be normally distributed. The latter group apparently is distributed, according to WEIBULL (1950), with the lower size limit located close to 10 μ. That this lower limit really exists is made probable by the fact that among the appr. 150 000 specimens which have so far been measured, none smaller than 13 $\ddot{u}$ were found.

The other type of distribution, which first attracted attention to the problems in question, is illustrated by fig. 1.9.2.3. The two populations mentioned above are still present, but several others with maxima in large sizes have attained quantitative importance. The conditions discussed above refer only to the percentage distribution and *a priori* nothing is known about the corresponding distribution of concentration of frustules. In order to elucidate this, size frequency determinations were carried out in aliquot portions of weighed samples (ch 4.9) which made possible the calculation of concentration and rate of accumulation of frustules in the size classes. The

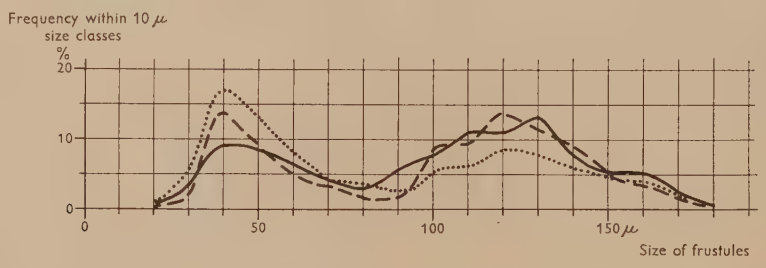

Fig. 1.9.1.2. Size-frequency distribution of *Coscinodiscus nodulifer* in two parallel samples of the sample 59—259. Full line; sample a, washed. Dashed line; sample b, washed. Dotted line; sample b, unwashed.

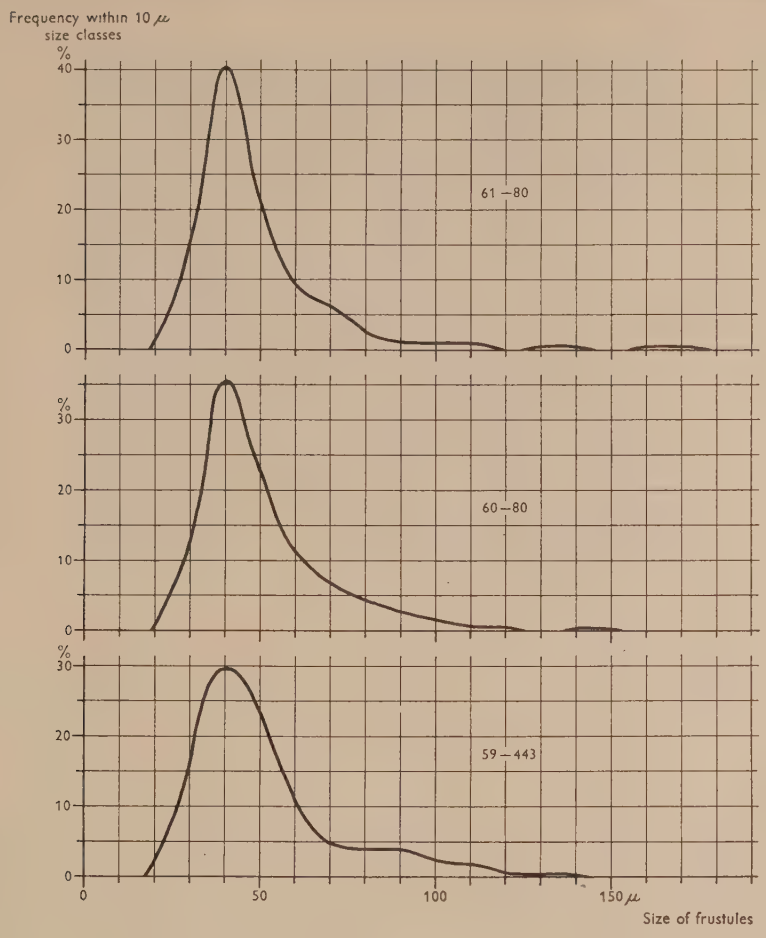

Fig. 1.9.2.1. Examples of size frequency distributions with a marked relative dominance in the size group 30—50 μ (odd-number stage type). The abscissae correspond to the upper limit of the 10 μ-size classes. The percentages found in these classes constitute the ordinates.

results are shown in fig. 1.9.2.4, which is based upon measurements of the diameter of 3 904 specimens in five samples. From this graph it appears that practically constant conditions prevail in the small size part (left part) of the distribution and that the maximum in the 30—50 μ area has a height slightly exceeding 100 000 specimens per 10 μ interval, cm² and 1 000 years except in the lowest stratum investigated where the rac slopes down slightly to just below the 100 000 — limit. The marked stratigraphical changes in size distribution affect only the large-size frequencies, and the change recorded in the stratum intercept investigated involves, in the medium and upper levels, the decline and disappearance of the large size maximum, which is well developed in the lower levels.

The general stratigraphical distribution of the changes in percentage distribution caused by changes of the rate of accumulation of large sized frustules is seen from pl. 2.39, 2.59, 2.60, 2.61, and fig. 2.62.9. The construction of the isoplethic diagram is described in § 1.0.3.

From these plates and figures it is evident that the recurrent development and disappearance of large-size frequency maxima in the *Coscinodiscus* distribution is a feature typical for the Equatorial carbonate facies and traceable in all equifacial sequences of this type, which have not suffered from far-reaching secondary dissolution of the diatoms. On the

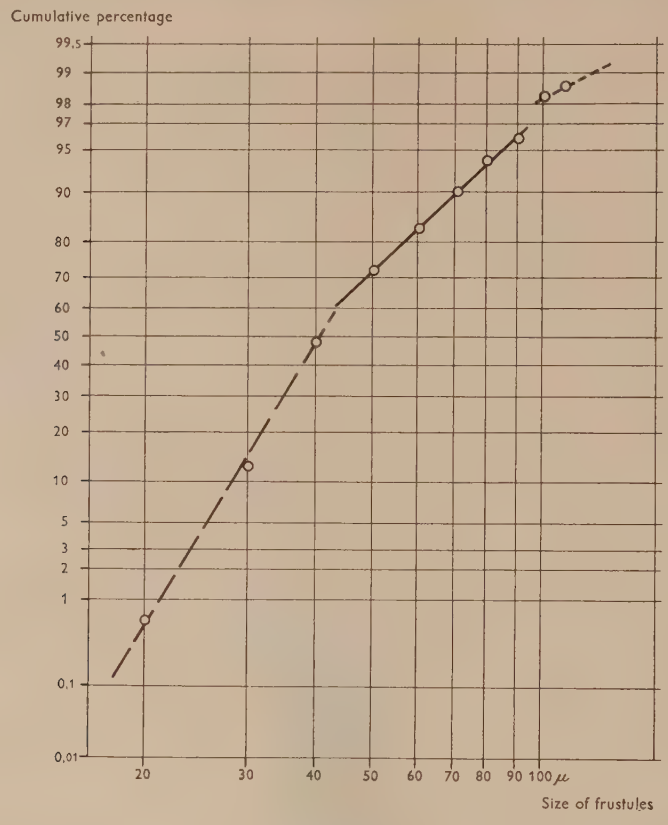

Fig. 1.9.2.2. The cumulative frequency values of the sample 60—80 (shown in fig. 1.9.2.1) plotted on normal probability paper. The two breaks in the curve indicate that at least three statistically different components are present, one consisting of the small amount of very large frustules, one of the group 50—90 μ and one of the frustules smaller than 40 μ. This latter group is believed to consist of the specimens which have passed the critical limit and lost their ability to form auxospores.

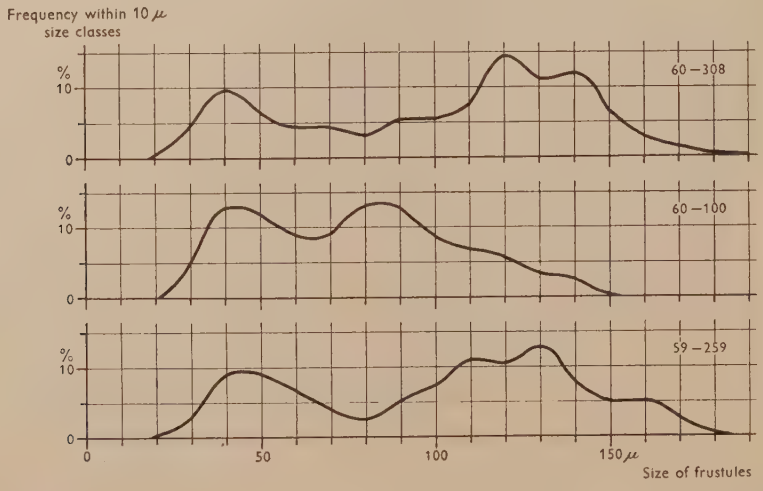

Fig. 1.9.2.3. Examples of size frequency distributions of the even-number stage type. Several secondary frequency maxima in large sizes have developed and owing to this the precentage of small frustules is considerably decreased.

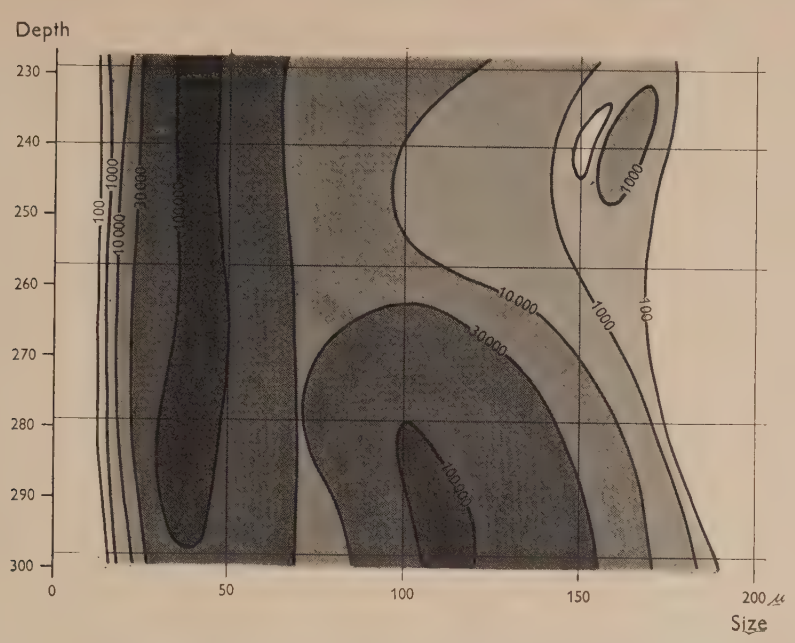

Fig. 1.9.2.4. Rate of accumulation of frustules as a function of size of the frustules and depth in the sediment (expressed in cm). The intercept of the sequence corresponds to the transition from stage 4 to stage 3 in core 60 and includes upper stage 4 and lower stage 3 (cf. pl. 2.60).

The curves of the graph indicate the number of frustules accumulated per cm^2 in 1000 years within each 10 - μ size interval.

The graph shows that the changes which cause the transition from stage 4 with a high rate of production to stage 3 with a low rate of production do not appreciably affect the rate of deposition of small sized specimens of *Coscinodiscus nodulifer*. This rate is practically constant throughout the strata investigated. The ecological changes, however, influence very strongly the rate of deposition of large sized specimens, so that the number of frustules 101—110 μ decreases from 112 000 per cm^2 in 1 000 years to 6 040 per cm^2 in 1 000 years; thus a reduction to 5.4 % of the maximum value.

East Pacific Ridge, such dissolution is a rule and a relatively undisturbed *Coscinodiscus* record is found only in core 39, which has a high rate of accumulation. Except in the East Pacific cores mentioned, the typical stratification with regard to size distribution of *Coscinodiscus nodulifer* has been found in equifacial sequences further to the west, viz. in the cores 74 (Lat. 0° 29′ S, Long. 151° 33′ W) and 75 (Lat. 0° 20′ N, Long. 150° 36′ W) and the changes are thus known to have taken place over an area with a minimum east-west extension of 6540 km.

It is further evident that the appearance of considerable amounts of large sized specimens is restricted to time-rock units, characterized by a strongly increased biogenous rate of accumulation. Finally it should be noted that the greatest maximum in large sizes occurs in stage 4 and the second greatest in stage 2.

1.9.3 Previous knowledge of the factors determining the size of the diatoms.[1])

A comprehensive treatment of the diatoms is given by Fritsch (1948) and Geitler (1932). At reproduction through cell division one of the new daughter cells retains the top valve (epitheca) and the other one keeps the slightly smaller bottom valve (hypotheca). Both daughter cells form a new complementary hypotheca. Of the daughter cells in the first generation one has thus the same diameter as the parent and the other a slightly smaller diameter. Thus in each generation is formed one daughter cell of reduced size. The reduction in size

[1]) The author is indebted to Dr. R. W. Kolbe for putting at disposal a critical survey of the literature in this field.

continues until a certain critical limit is attained, when the auxospore formation sets in. The auxospore generally produces an individual of larger size than that, which formed the auxospore. If this is not formed when the critical size is reached, the decrease in size appears to continue until a minimum limit is attained, when the cells die.

The auxospore formation of the *Pennales* has been studied thoroughly. It has been definitely stated that an auxospore is always the result of a sexual process; diploid mother cells undergo a meiosis and haploid gametes are formed which conjugate and produce diploid zygotes (auxospores). The parental valves are thrown off, the auxospore grows out and a new silicified frustule is formed within, which is usually larger than the parental one.

According to WIEDLING (1948) the auxospore formation is not always necessary in order to secure a constant medium size of a population. This was demonstrated in certain *Nitzschiae* which retained their medium size during many years of pure culture without ever producing auxospores.

Our knowledge of the auxospore formation of the *Centrales* is still very incomplete. Until recently the general opinion was that the auxospores of the *Centrales* were formed asexually and that their formation involved a rejuvenescence of the protoplast. This thrusts apart the parental valves, becomes enveloped in a thin, slightly silicified pectic membrane, the perizonium, within which it undergoes a rapid enlargement. A new frustule is secreted inside the perizonium and a new individual, larger than the parent is produced.

Modern investigations (e. g. PERSIDSKY 1929, IYENGAR and SUBRAHMANYAN 1944) make it very probable that the *Centrales* behave in the same way as the *Pennales* and that their auxospores too are formed by a primitive sexual process. The diploid mother cells undergo a reduction division prior to the formation of the auxospore and four (haploid) nuclei are produced. At least two of these conjugate inside the mother cell. The product of their fusion is the diploid auxospore (zygote).

A process, which is apparently restricted to the *Centrales*, is the formation of microspores. Although frequently recorded, the cytological details are still uncertain. PERSIDSKY'S (o. c), e. a. investigations indicate that a sexual process is involved but whether the microspores are haploid gametes or diploid zoospores could not be proved so far.

As to the physiology of auxospore formation it was previously believed that the only condition stimulating the production of auxospores were the reduction of the cell to a certain minimum size. Recent investigations by GEITLER o. c., however, demonstrated that the auxospores are not formed by the smallest individuals of a population and that some hitherto unknown physiological or ecological conditions appear to influence the formation of auxospores. The present results indicate that auxospore formation in an early stage of the vegetative part of the reproduction cycle (large sized individuals) is favoured by the same factors which promote a temporarily increased phytoplankton production in the East Equatorial Pacific (increased supply of nutrients by upwelling deep water). This makes it possible that the changes in tendency to auxospore formation might ultimately be due to the differences in energy requirements for mitosis on one hand and meiosis on the other.

1.9.4 Interpretation of the results.

The size frequency distributions obtained indicate that the normal critical limit of *Coscinodiscus nodulifer* is located between 30 and 50 μ, that the minimum size limit is appr. 13 μ and that the size of the postauxospore frustule can be very high (appr. 200 μ). The development of secondary large-size frequency maxima is believed to indicate a tendency to auxospore formation already in larger sizes than normal.

The facts, which are of importance from stratigraphical and paleoecological points of view, are that the occurrence of large-size frequency maxima in the size distribution of *Coscinodiscus nodulifer* are connected to a high rate of production and accumulation of individuals of this species, of other diatoms, foraminifera, and probably coccolithophorides. This relationship is demonstrated in fig. 1.9.4, which is based on the same material as fig. 1.9.2.4. The ordinates correspond here to the rates of accumulation of frustules of *Coscinodiscus nodulifer* of all sizes and the abscissae to the amounts of frustules $> 70\ \mu$, expressed as a percentage of the total amount of frustules.

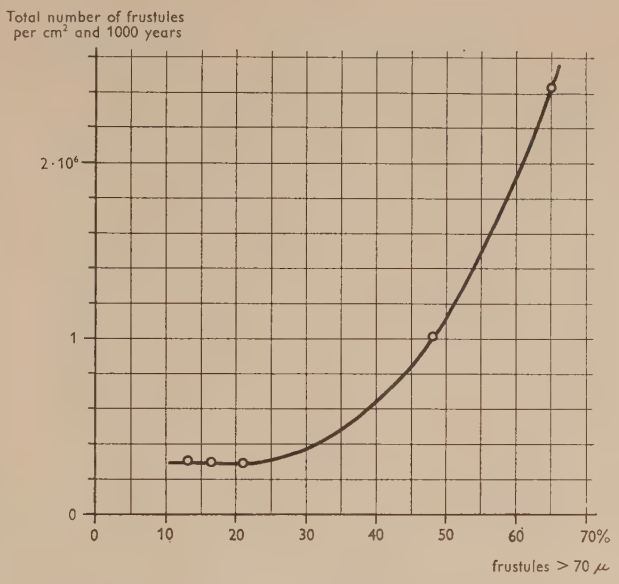

Fig. 1.9.4. Relationship between the total rate of accumulation of frustules of *Coscinoduscus nodulifer* and the percentage of frustules larger than 70 μ of this species. The graph demonstrates that if the percentage of frustules larger than 70 μ exceeds appr. 40 %, the excess can be taken as a measure of the total rate of accumulation (= appr. rate of production in this environment) of frustules of *Coscinodiscus nodulifer*.

As the *Coscinodiscus* frustules are subject to dissolution to a far smaller extent than the calcareous structures, it is believed that the rate of accumulation of these siliceous frustules gives a still better record of the rate of production at the surface of the ocean than does the rate of accumulation of $CaCO_3$ (ch. 1.1). The relative extent of the percentage increase in large frustules of *Coscinodiscus nodulifer* therefore facilitates at least a qualitative comparison of the rate of phytoplankton production and thus presumably of the rate of upwelling and circulation in the even-number ages. The results indicate that, of all recorded Pliocene and Pleistocene ages with an increased rate of circulation, the last four or five were characterized by a higher maximum rate than the preceding ones. Of these Upper Pleistocene ages with a strongly increased intensity of circulation, the next to the last one (age 4) is unsurpassed with regard to this intensity. The last age with an increased circulation (age 2) is comparable to age 4 but appears to have had a lower increase than the latter. The conditions found in stages 6, 8 and 10 indicate rates of circulation higher than in the Lower Pleistocene but not comparable to the corresponding rates in stages 4 and 2. This is in agreement with the evidence arising from the composition of the planktonic foraminiferal assemblages. These are characterized by a higher percentage of assumed warm-water forms in the Pliocene and in the even-number stages of the Lower and lower part of Upper Pleistocene than in the latest stages of increased circulation.

Besides the use that can be made of the size frequency distribution of *Coscinodiscus nodulifer* for estimating the relative production and circulation intensities, this distribution is very useful at the stratigraphical identification and subdivision of the Upper Pleistocene time-rock units, especially stages 2 and 4.

1.10 Other fossils

1.10.1 Scope and limitation of the study.

In the East Pacific calcareous sediments only foraminifera, radiolaria, diatoms and coccolithophorides were studied quantitatively. Occurrences of single specimens or small

amounts of fish vertebrae, echinoid spines, ostracode shells, fish teeth, scales and otoliths, annelide jaws and faecal pellets, have been mentioned in connection with the description of the cores (part 2) and the last group also in connection with reworking (§ 1.12.5).

In the pelagic clays, fossil groups that are not easily studied quantitatively in the calcareous deposits are concentrated, and could be included in the routine coarse fraction analysis. These groups are sponge remains, fish teeth, and annelide jaws, and »mollusc fragments» (cf. § 4.9.1).

All concentrations are expressed as number of specimens per g dry, salt-free sediment.

1.10.2 Sponge remains.

The sponge spicules, owing to their massive structure and large dimensions, are less sensitive to peptization of the silica than are the radiolaria and the diatoms. Still, corrosion traces are obvious also in the siliceous skeletons of spongiae, e. g. in core 48. Peptization, however, less often than in radiolaria appears to lead to the complete disappearance of the fossil. The number of sponge spicules per g sediment is therefore believed to give a truer representation of the original distribution than the corresponding number of radiolaria. Core 48, where peptization of silica is far advanced, forms an exception, and in this case not even the sponge remains are considered to reflect the original concentration of siliceous remains.

The frequency distribution of sponge remains in the North Equatorial clay and silica facies is shown in fig. 1.10.2.1. The geographical location of the cores is seen from fig. 1.0 (inserted at the end of part 1, 2 and 3). The frequency distribution illustrates the low concentration of spongiae in the North clay (core 51), gradually increasing to the south, until very high concentrations are attained in the siliceous clay (core 55, 56, 57) bordering the Equatorial carbonate area and extending

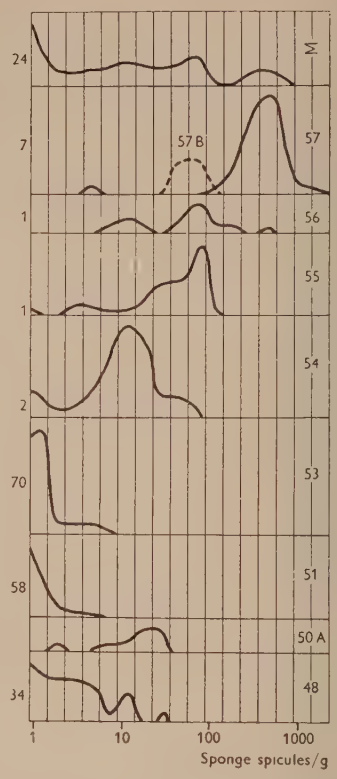

Fig. 1.10.2.1. Frequency distribution of sponge spicules in the North Equatorial clay cores (core numbers indicated to the right in the diagrams). The figures to the left in the diagram indicate the percentage of samples with a content lower than 1. The top diagram represents the average distribution. The class interval is indicated by the grid.

below the fertilizing North Equatorial Divergence. Further, the calcareous Tertiary sediments of cores 53 and 57 differ widely with regard to the content of siliceous sponges; core 53 displays the very low concentrations, typical of the present North clay facies, whereas core 57 is characterized by the very high concentrations which indicate the vicinity of a zone of upwelling. This is thought to indicate that the present pattern of surface currents was established before the time corresponding to the Tertiary strata (presumably older than Pliocene and younger than Oligocene). This conclusion is, however, not definite as the calcareous Tertiary strata of cores 53 and 57 appear to be metachronous, the former being the older (cf. ch. 3.3).

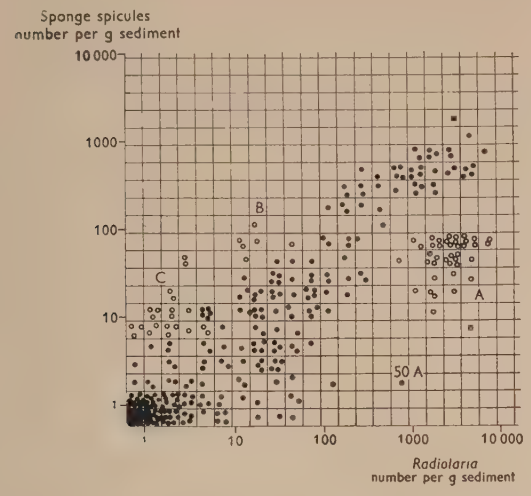

Fig. 1.10.2.2. Relation between concentration of siliceous sponge remains and concentration of radiolaria. Each point corresponds to one sample. The location of the points within the grid squares is not defined. Groups A, B and C are indicated by open circles.

The relation between sponge remains and radiolarian skeletons is believed to give some information with regard to the state of preservation of the latter. This relation is shown in fig. 1.10.2.2. The normal posthume equilibrium may be described as an exponential relationship of the type $s = r^k$, where s is the concentration of sponge remains, r the concentration of radiolaria and k a constant which is positive and slightly smaller than 1. Samples that have not been subject to normal peptization are located to the right (group A) of the average distribution, whereas samples with an abnormally far-reaching peptization of the radiolaria are distributed to the left in the diagram (groups B and C), provided that the sponge spicules have not suffered from corrosion to a corresponding degree. Group A consists of the samples from the Recent and Subrecent top stratum (cores 50 A, 55 B, 57 B, and the tops of cores 55 and 56). B includes the samples below the unconformity in core 56 (cf. ch. 2.56) and C corresponds mainly to the oldest strata of core 54 (below 565 cm). The state of peptization of the radiolaria, as indicated by these relationships, is believed to be of value when judging the presence or absence of the Recent and Subrecent top strata of pelagic clay cores.

1.10.3 Fish teeth and annelid jaws.

No attempt was made to distinguish between these two fossil groups or to carry out closer taxonomic subdivisions. All specimens are thus reported as fish teeth in the column headings of table 2.48—2.57 and in the following text. No traces of corrosion were observed, but on the other hand no systematic search for such traces was carried out.

The frequency distribution of teeth is shown in fig. 1.10.3.1. From this graph it is seen that the concentration is mostly very low and

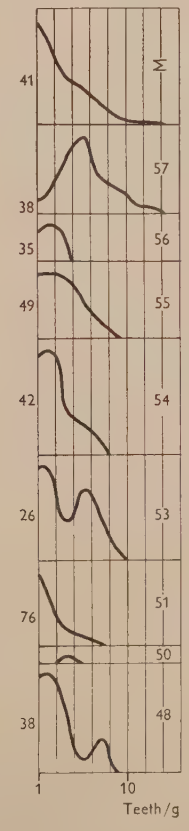

Fig. 1.10.3.1. Frequency distribution of fish teeth and annelide jaws in the North Equatorial clay cores (core numbers indicated to the right in the diagrams). The figures to the left in the diagram indicate the percentage of samples with a content lower than 1. The top diagram represents the average distribution. The class interval is indicated by the grid.

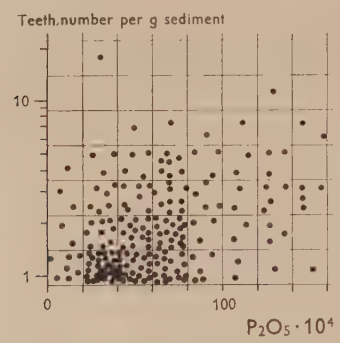

Fig. 1.10.3.2. Relation between concentration of fish teeth and of phosphorus. For construction of the diagram, see fig. 1.10.2.2.

exceeds 10 per g only in a few samples from core 57, below the North Equatorial Divergence. It should be pointed out, however, that considerable amounts of teeth appear to be smaller than 150 μ. Thus the values reported here represent only the large sized teeth. Secondary maxima in intermediate concentrations occur in core 48 from the East Pacific Ridge and in the calcareous Tertiary of core 53. The relatively high values in core 48 are, as in most cores from this area, derived from the phosphatic Tertiary strata.

This fact indicates the possibility of the phosphorus being largely derived from fish teeth. In order to check this possibility the relation between concentration of teeth and of phosphorus was investigated graphically. This relation is shown in fig. 1.10.3.2. The high dispersion of the values is believed to indicate that there is no direct relationship between the two properties.

1.10.4 »Mollusc fragments».

»Mollusc fragments» consist of broken and corroded pieces of semitranslucent, mostly opalescent curved calcareous structures of unknown origin. No entire structures or fragments big enough to enable an identification, were found. The curvation of the fragments make it probable that the original objects were smaller than appr. 1 cm. The »mollusc fragments» may be derived from pteropode shells or fish bones. Their frequency distribution, shown in fig. 1.10.4, give the same general impression as the distribution of other fossil groups, viz. a relatively high concentration in the siliceous clay below the production area of the North Equatorial Divergence (cores 48, 50, 56, and 57) and a low content in the North Clay. The calcareous Tertiary core 53 is comparatively rich in these fossil fragments. This may be an original feature but may also be caused by the protective effect of the chalk and marl ooze against posthume dissolution. That the »mollusc fragments» are liable to such dissolution is indicated by the vertical distribution, e. g. in core 48 (pl. 2.48, col. »mollusc fragments»).

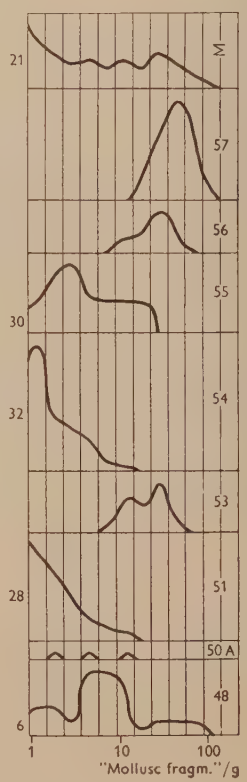

Fig. 1.10.4. Frequency distribution of »mollusc fragments» in the North Equatorial clay cores (core numbers indicated to the right in the diagrams). The figures to the left in the diagram indicate the percentage of samples with a content lower than 1. The top diagram represents the average distribution. The class interval is indicated by the grid.

1.11 Rock fragments and mineral grains.

1.11.1 Scope and limitation of the study.

In the microscopic analysis of the grain fractions $> 150\,\mu$, all objects observed were counted and recorded. Rock fragments and mineral grains were tentatively divided into three groups, viz. glass and palagonite, manganese micronodules, and »other mineral grains». As the microfossils, which were the main objects of the analysis, were studied in reflected ordinary light it was not always possible to make a clear distinction between the first and third groups. Control analyses revealed that in cases where small, translucent and massive fragments of glass occur, these have been counted as »other mineral grains». In most cases no attempts have been made to carry out a continued subdivision of rock fragments and allogenic mineral grains, as the concentrations are in most cases very low, and as a satisfactory study of these constituents require a quantitative microscopical investigation also of grain sizes smaller than $150\,\mu$. For practical and economic reasons such an investigation could not be included in the present program. The fine washings of the 1 g samples used for microscopic coarse-fraction analysis have, however, been quantitatively recovered and stored for future investigations.

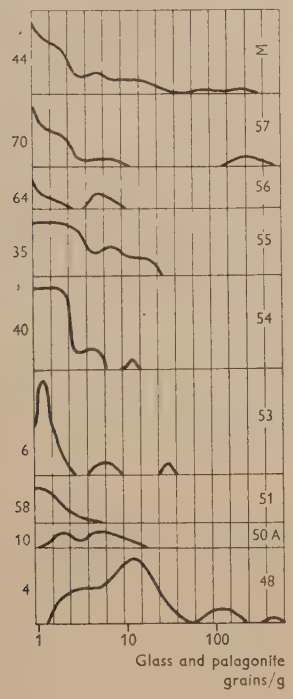

Fig. 1.11.2.1. Frequency distribution of glass and palagonite in North Equatorial clay sediments. The core numbers are indicated to the right in the diagrams. The figures to the left indicate the percentage of samples with a content lower than 1. The top diagram illustrates the average distribution of all samples from this area. The grid corresponds to the class interval. For construction of the diagram, s. § 1.0.3.

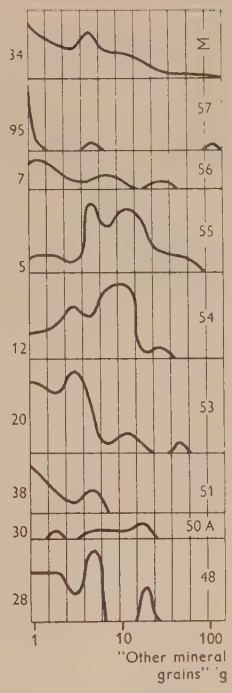

Fig. 1.11.2.2. Frequency distribution of »other mineral grains» in the North Equatorial clay cores (core numbers indicated to the right in the diagrams). The figures to the left in the diagram indicate the percentage of samples with a content lower than 1. The top diagram represents the average distribution. The class interval is indicated by the grid.

1.11.2 Glass, palagonite, and »other mineral grains».

The frequency distribution of glass and palagonite in North Equatorial clay and silica facies is shown in fig. 1.11.2.1 and of »other mineral grains» in fig. 1.11.2.2. As is seen from these, the concentrations are mostly very low and a content of 100 grains/g sediment

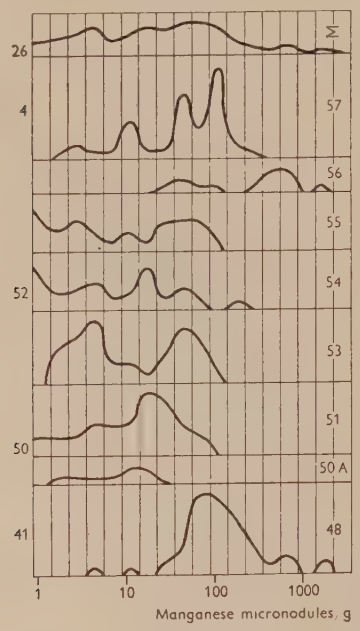

Fig. 1.11.3. Frequency distribution of manganese micronodules in the North Equatorial clay cores (core numbers indicated to the right in the diagrams). The figures to the left in the diagrams indicate the percentage of samples with a content lower than 1. The top diagram represents the average distribution. The class interval is indicated by the grid.

is attained only in core 48 (basal stratum) and in a few levels of core 57. In the former case the material appears to be autochthonous or transported only a short distance (ch 2.48). In the latter case, however, it appears most probable that the material was air- or water- borne and possibly transported over large distances (§ 2.57.11).

It is possible that the group »other mineral grains» contains not only allogenic mineral grains but also single prisms of phillipsite and possibly other authigenic minerals. Aggregates of phillipsite, such as were found in the minerolytic sediments of the South Archipelagic area (fig. 1.0.) and described o. a. by MURRAY and RENARD (o. c.), were not found in the East Eupelagic area and only in rare cases in the East Pacific Ridge deposits.

1.11.3 Manganese micronodules.

The concentration of manganese nodules is an expression of the state of dispersion of the manganese and is only indirectly related to the total amount of manganese in the sediment. The distribution of total manganese and manganese nodules $> 150\,\mu$ will be treated in detail elsewhere, and only a brief account of the latter will be given here.

The frequency distribution of manganese micronodules $> 150\,\mu$ in North Equatorial clay and silica facies is shown in fig. 1.11.3. Very high contents are found in cores 56, 48 and 52 (the latter core not being represented in fig. 1.11.3 because of the small number of samples; cf. ch. 2.52). In core 56 the manganese is believed to be almost entirely of halmyrogenous origin (§ 1.12.6). The high concentrations are either due to a low rate of minerogenous accumulation or to a high rate of manganese accumulation in the lower part of the sequence which is confined upwards by an unconformity. This explanation is applicable also to cores 53 and 57. The manganese found in cores 48 and 52 is believed to be of largely minerolytic origin, as in both cases great amounts of weathering basaltic glass are present in levels close to those where the nodules are found to be frequent. If the interpretation of the phosphatic stratum of core 48 as an equivalent to those found in eupelagic clay cores is correct, halmyrogenous manganese might be assumed also to contribute to the high content of total manganese and of nodules found in the stratum in question.

1.12 Salinity, water, and density relations. Diagenesis of the sediment.

1.12.1 Salinity and water content.

Methodical studies of the water content — chlorinity relationship were carried out in two strongly indurated cores from the East Pacific Ridge, in samples of varying calcium carbonate content from the East Eupelagic area, and in 835 samples from Atlantic cores analyzed with regard to water content by Prof. A. Hadding, Lund, and with regard to

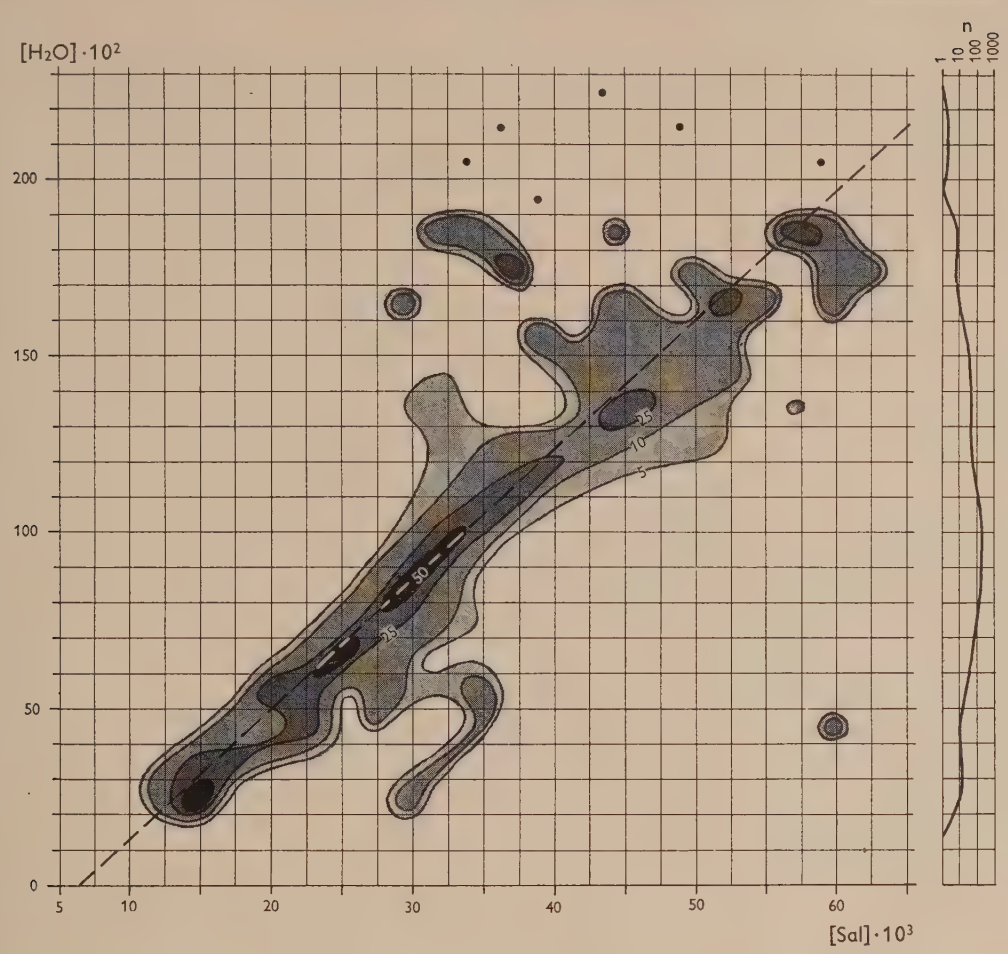

Fig. 1.12.1.1. Relationship between salinity (S_{105}) and water content (W_{105}), the former values taken over from Gripenberg and the latter recalculated from Hadding's analyses. Values outside the 5 % equiprobability curve have been indicated by points. The dashed line corresponds to the equation $W_{105} = 3.7 \cdot S_{105} - 24$. The right diagram illustrates the number of samples in each group of water values (each horizontal series of squares). For the construction of the isoplethic diagram, see § 1.0.3.

chlorinity by Dr. S. Gripenberg, Göteborg.[1]) The results gained from Hadding's and Gripenberg's material (fig. 1.12.1.1) indicate that as a general rule there is a good and linear correlation between the salinity (as calculated from the chlorinity) and the water content of the sediment. A restricted number of samples deviate markedly from the linear relationship. As the Atlantic cores have not yet been investigated stratigraphically it is difficult to decide the reason for the deviations. It is assumed, however, that these are due to diagenetical changes as this has been found to be the reason for deviations in the East Pacific Ridge deposits. If these abnormal values are neglected, the relationship best fitting to the analytical results is estimated to be

$$W_{105} = 3.7 \cdot S_{105} - 24 \qquad (1.12.1.1)$$

where W_{105} is the loss of water expressed as percentage of salt-free sediment dried at 105° C, and S_{105} is the salinity calculated from the chlorinity and expressed as the fraction of salt $\cdot 10^3$ of salt-free sediment dried at 105° C. The equation (1.12.1.1) can be recalculated for water content and salinity determined in samples dried at 20° C, as was done in the

[1]) Published by courtesy of these workers.

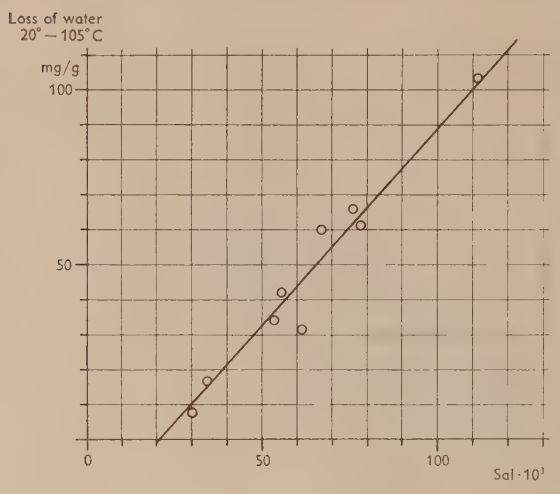

Fig. 1.12.1.2. Relationship between salinity (S_{20}) and loss of water at heating from 20° C (10.5 T_{H_2O}) to 105° C. Values from table 1.12.1.

present work, (cf. ch. 4.7) if the loss of water between 20° and 105° C is known. The measurements on eupelagic samples shown in table 1.12.1 and fig. 1.12.1.2 indicate a close relationship between salinity (col. 3) and loss of water (col. 5) viz.

$$H = 0.11\,S - 2.3 \qquad (1.12.1.2)$$

where H is the loss of water between 20° and 105° C expressed as percentage of the weight at 105° and S is the salinity as defined in ch. 4.7 and expressed in the unit 10^{-3}. Further

$$S = 1.07 \cdot S_{105} \qquad (1.12.1.3)$$

Using the relationships (1.12.1.2) and (1.12.1.3), (1.12.1.1) is transformed to

$$W = 3.3 \cdot S - 22 \qquad (1.12.1.4)$$

where W is the loss of water of samples dried at 20° C and 10.5 T_{H_2O}, expressed as percentage of the dry, salt-free sediment.

If instead the values from the East Pacific Eupelagic area are used for the calculation (values from table 1.12.1) we obtain

$$W = 3.1 \cdot S - 26 \qquad (1.12.1.5)$$

which is in fairly good agreement with eq. (1.12.1.4). If Atlantic water contents are calculated from Pacific salinities or vice versa, an error arises which varies between 7 and 10 % of the water content. The Atlantic equation (1.12.1.4) is based on a great number of determinations but the samples of this material have not yet been tested with regard to their eupelagic character and the amount used for analysis was relatively small (0.3—1.0 g dry weight), which tends to increase the scattering due to inhomogeneity of the material. — The Pacific equation (1.12.1.5) is based on

TABLE 1.12.1

1	2	3	4	5	6	7	8	9	10		
Sample Core Depth	$CaCO_3$ %	Sal · 10^3	Water % of dry, salt-free sediment	Loss of water 20°—105° C % of weight at 105° C	Weight of unit volume, wet.	Weight of unit volume, dry.	Pore volume of wet sediment % $\left(\frac{100 \cdot \text{vol } H_2O}{\text{vol of wet sample}}\right)$	Average density of dry residue at 20° C and 10.5 T_{H_2O}	Wet volume of unit weight dry, salt free sediment at 20° C, 10.5 T_{H_2O} (A)		
									found	Calculated from water content	Calculated from salinity
57— 130	0	111	318	10.3	1.185	1.018	84	2.21	3.64	3.64	3.65
58— 659	23	76	208	6.6	1.257	0.717	83	2.33	2.51	2.51	2.53
58— 431	30	78	207	6.1	1.267	0.725	83	2.37	2.49	2.50	2.60
58— 622	40	67	205	6.0	1.264	0.724	83	2.41	2.47	2.48	2.24
58— 920	52	56	134	4.2	1.366	0.886	76	2.42	1.75	1.75	1.89
59— 434	60	61	152	3.2	1.341	0.680	79	2.41	1.94	1.93	2.05
62— 162	69	53	134	3.4	1.371	0.706	77	2.47	1.75	1.75	1.80
62— 1170	80	34	83	1.7	1.524	0.963	68	2.57	1.22	1.22	1.19
62— 34	92	30	70	0.8	1.597	1.015	65	2.60	1.08	1.09	1.06
										$\sigma = 0.007$	$\sigma = 0.112$

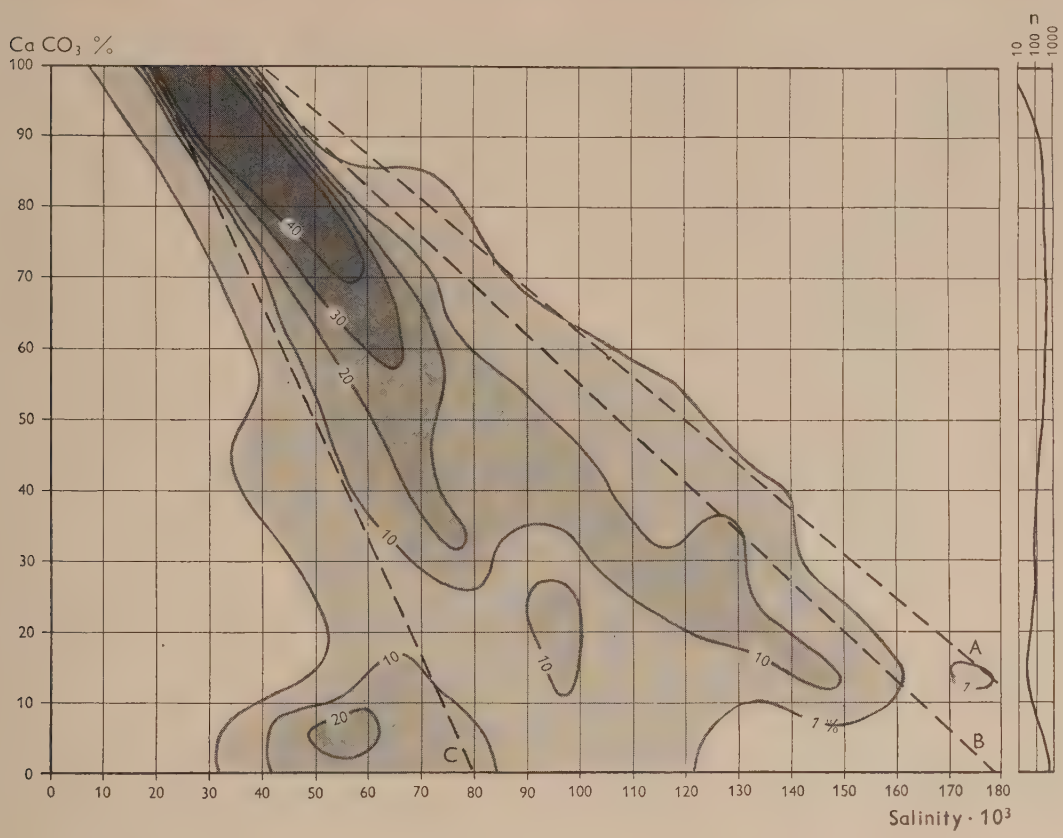

Fig. 1.12.2.1. Relationship between salinity and content of calcium carbonate in all East Pacific samples. The approximate upper boundary of the distribution is represented by the guide line A. The lines B and C are taken over from fig. 1.12.2.2.

a comparatively small number of analyses, but these were run in duplicate, the amount of material used for the analysis was relatively great (5—14 g dry weight) and the material was controlled with regard to the conditions of deposition (ch. 1.2). As it might further be assumed that the 7—10 % difference between the two equations arises from principal differences in the sediments from the two oceans, it was regarded as most correct for the present purposes to use the equation (1.12.1.5). The standard error inherent in this equation is treated in connection with the equation (1.12.3.2) below.

1.12.2 Calcium carbonate — salinity relationship.

From the plates 2.39—2.62 is seen that there is mostly a negative correlation between calcium carbonate content and salinity.[1]) This correlation has been investigated in each core separately (§ 2.39.12—2.62.12). The composite relationship $CaCO_3$ — Sal is shown in fig. 1.12.2.1, which comprises all East Pacific samples and in fig. 1.12.2.2, which contains the East Eupelagic samples. From these is seen that the salinity of pure chalk oozes is fairly constant (appr. $30 \cdot 10^{-3}$) whereas the salinity of the calcium carbonate free component of the sediment varies greatly (from slightly more than 30 to the extrapolated value $200 \cdot 10^{-3}$). As has been demonstrated in the preceding paragraph, the salinity is a linear function of the water content of the sample except in such cases where

[1]) According to personal communications, the correlation between salinity and carbonate content has been observed also by Dr. B. Kullenberg and Dr. J. D. H. Wisemann.

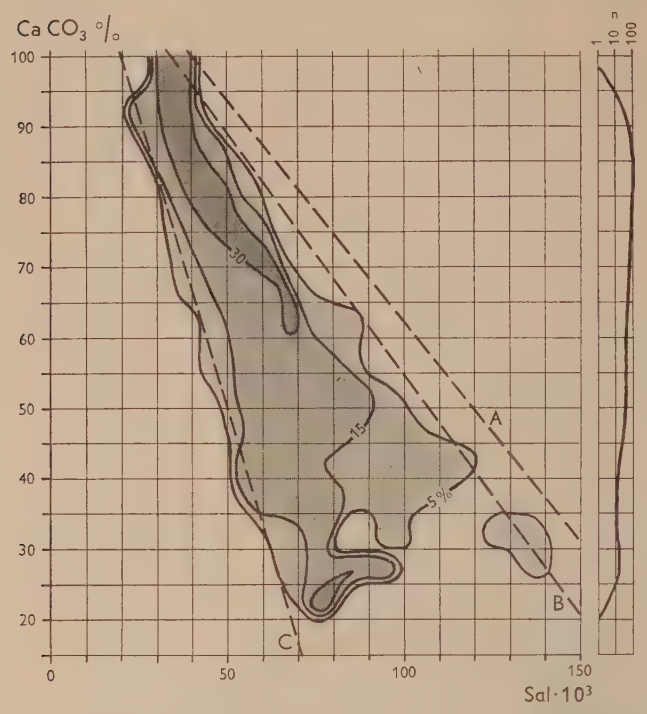

Fig. 1.12.2.2. Relationship between salinity and content of calcium carbonate in calcareous samples from the East Eupelagic area. The lines B and C represent the approximate boundaries of the distribution.

extensive induration has changed the normal relationship. At least in the East Eupelagic area the correlation between calcium carbonate and salinity has its origin in a close relationship between calcium carbonate and water content. This relationship is not surprising as it has long been a well known fact that clays have a great sorption capacity in contrast to calcium carbonate, which is a poor sorbent of water, owing both to its lattice structure and to the saturation of the particle surfaces with calcium ions, which are poorly hydrated. The adsorption equilibrium attained in the deposits investigated appears in most cases not to be markedly influenced by the pressure exerted by a cover of sediment up to ten meters thick (cf. § 1.12.7).

An interesting feature of the calcium carbonate-salinity distribution found is the varying salinity of the calcium carbonate free component of the deposit. In sediments which have been subject to extensive secondary induration this appears to have influenced also the salinity (§2.41.12, § 2. 42.12), but this influence does not result in a marked displacement of the regression line but in a strong scattering of the values (e. g. fig. 2.41.12). Further it is seen from the figures 2.39.12—2.62.12 that there are distinct differences in the regressions of different sediment types. It is therefore concluded that the variations from core to core or within the cores in the average salinity of the calcium carbonate-free component is not due to secondary displacement of the sea salts in the interstitial solution or to diagenetical changes in the composition of the salt.

Fig. 1.12.2.3 shows the frequency distribution of salinity in North Equatorial Pacific clay and silica facies (core 48, East Pacific Ridge, silica facies, 50, 51, 52, and 54, eupelagic clay facies, 55, 56, and 57, eupelagic silica facies). It is evident that a high salinity (and water content), is a characteristic feature of the carbonate-free siliceous sediments bordering the North Equatorial carbonate area, whereas the purer eupelagic clays are poor in salt (and water). Finally it is seen from fig. 1.12.2.1 and 1.12.2.2 that the calcium carbonate-free component of the calcareous sediments, which have a still higher ratio of biogenous silica to clay than the carbonate-free siliceous oozes investigated, has also a still higher salinity than these. From these facts it is concluded that the salinity of the calcium-carbonate-free component is in some way related to the concentration of biogenous silica. A statistical correlation of the amount of salt per unit mass of calcium-carbonate-free matter with the calculated percentage of biogenous silica revealed, however, that there is no quantitative relationship between these two properties. As a probable explanation it is

suggested that the decisive factor in this case is not the amount of biogenous silica but the fraction of this, present as colloidal silica, derived from siliceous structures through peptization of these (cf. § 1.12.4 and 1.12.6). This explanation is tentative.

1.12.3 Volume weight relationships.

In the series of eupelagic samples (table 1.12.1) selected so as to cover the entire range of calcium carbonate content, the wet volume and weight, and the dry volume and weight were also determined. The wet volume was determined by weighing the sample in decahydronaphtalene, and the dry volume by weighing the sample in water after covering it with a film of rubber latex of known weight and density.

From table 1.12.1 is seen that there is a linear relationship between the density (col. 9) and the water content of the sediment (col. 4) in spite of the varying mineral composition of the samples. This is not surprising as both density and degree of hydration of the deposit are determined by the amount of clay minerals and biogenous silica in relation to the amount of poorly hydrated minerals (here = calcite). Thus there is also a fairly good linear relationship between the content of calcium carbonate on one hand and the water content, salinity and average density on the other.

The relationship between the wet volume and the dry weight of the sediment is of stratigraphical importance, as it determines the conversion of analytical results, expressed as mass per unit mass, to mass per unit length of the sedimentary column and ultimately to mass per unit time (ch. 1.2). Thisr elationship has a. o. been treated theoretically by Koczy (1951) who suggests a calculation of the density of the wet sediment from the density of the dry sediment under the assumption that the volume of the wet sediment is equal to that of the dry sediment + the volume of the water. There are, however, two reasons for

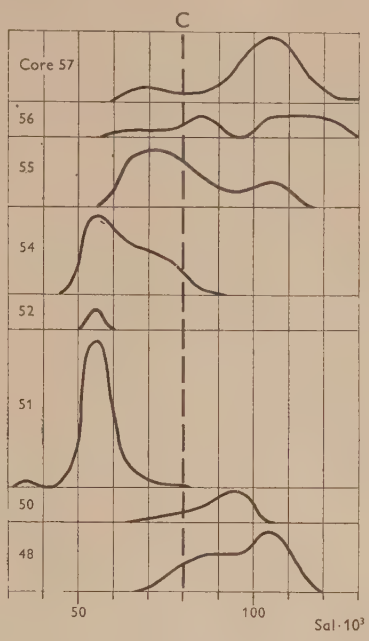

Fig. 1.12.2.3. Frequency distribution of salinity in North Equatorial Pacific clay and silica facies. The core numbers are indicated to the left in the diagram. The surfaces below the curves correspond to 100 % of the number of samples. For location of the cores, see fig. 1.0. — Siliceous oozes are rich in salt (water) whereas pelagic clays are comparatively poor.

using other methods for the determination of the density of the wet sediment. The assumption used is not applicable to sediments containing swelling clay minerals (cf. MARSHALL, 1949, p. 162). Further, great practical difficulties are involved in the determination of the density of dry powders, especially if these are strongly adsorbent. In the present case the density of the wet sediment was determined by direct determination of the weight and the volume of the wet sample, this method being both simple and accurate.

An important consequence of the fact that the hydration equilibrium is dependent on the mineral composition of the sediment is that the density of the wet sediment is uniquely determined by the water content in the East Pacific calcareous eupelagic sediments investigated. Thus the relationship between the water content expressed as percentage of dry, salt-free sediment (W, col. 4, table 1.12.1) and the

wet volume of a unit weight of dry, salt-free sediment (A, col. 10.1) was determined by the method of least squares and was found to be

$$A = 0.01028 \cdot W + 0.368 \qquad (1.12.3.1)$$

with a standard error of $A = 0.007$ (table 1.12.1, col. 10.2), which corresponds to 0.6 % of the lowest and 0.2 % of the highest value of A. As the water content of normally indurated eupelagic sediments is in proportion to the salinity of the sediment as calculated from the chlorinity (eq. 1.12.1.5), the equation (1.12.3.1) can be transformed to

$$A = 0.032 \cdot S + 0.10 \qquad (1.12.3.2)$$

if S is the salinity expressed in the unit 10^{-3}.

The values of A calculated from the salinities have been entered in table 1.12.1, col. 10.3. The standard deviation of A, thus calculated, amounts to 3 % of the maximum value of A and 10 % of the minimum value. This theoretical maximum percentage error might, however, probably not be attained, as the great deviations appear to be concentrated to samples of medium water content, i. e. to marl oozes.

For the purpose of conversion of the analytical results from a mass to a volume basis was used the factor q

$$q = \frac{1\,000}{A} = \frac{31\,250}{S + 3} \qquad (1.12.3.3)$$

which expresses the number of milligrams of dry, salt-free sediment per ml of wet sediment. S is the salinity, multiplied by 10^3. In a sedimentary column with a cross section area of 1 cm^2, q expresses the number of milligrams of dry, salt-free sediment per cm of length of the column and $P \cdot q \cdot D$ is the number of milligrams of an element with the mass concentration P in a column with a length of D centimeters.

In connection with the density relationships, the great pore volume of pelagic lutite sediments (table 1.12.1, col. 8) should be stressed. This property might be of importance for the diffusion of solutes through the sediment. It should be noted, however, that the pore water is not free but constitutes the hydration water of the lutite constituents. The sediment might therefore largely be looked upon as a gel saturated with water. The calcareous sediments on the other hand, which are less strongly hydrated might also contain capillary and gravitational water, the latter enclosed in foraminiferal tests. It is thus possible that pelagic clays have more extreme ultrafilter properties than pelagic chalk oozes under comparable pressure conditions in spite of the smaller pore volume of the latter type of sediment. No experimental investigations of these conditions were carried out in connection with the present work.

1.12.4 Strength.

Two main types of diagenetical induration occur in the present material. One, which is here called the normal type of induration, might be described as a linear increase of the logarithm of the strength with depth. The type example is core 51, where the average strength logarithm rises from 1.56 at 0 cm to 2.28 at 10 m. The line connecting these two points has been entered as a comparison in pl. 2.38—2.62. It should be stressed that the linear illustration of the increase of the log strength is used for comparative descriptive purposes. The present material is not believed to allow conclusions with regard to the details of the induration as a function of depth, as the sampling technique appears to cause mechanichal disturbances, especially when long cores are collected. Theoretical considerations make it probable that the increase of the logarithm of the strength is in fact a linear function of the logarithm of the depth rather than of the depth. — Superimposed upon the regular increase of strength with depth are variations caused by the stratification of the deposit and by the mechanical inhomogenity due to digging

structures. Thus clayey sediments generally have a lower strength than chalk oozes of comparable age, especially if the chalk ooze is fine grained. Cores 39, 51, 54, 58, 59, and 60 are regarded as representative of the normal type of induration. In core 61, which has a high rate of accumulation, the strength is appr. constant down to 6.5 m where the increase starts. In core 62 the regular increase is also delayed and starts first below 5 m. Above this level there are abnormally indurated strata, one above 0.7 m and one between 4.2 and 4.8 m.

The normal induration cannot be explained as caused by expulsion of water due to compaction, as this effect is hardly traceable in the pelagic sequences investigated (§ 1.12.7). Nor can it be explained by a time-dependent peptization of the siliceous structures and cementation of the sediment with the peptized silica, as in several eupelagic calcareous cores diatoms, which are very sensitive to corrosion, are found uncorroded also in the lowest strata of the columns. Further, in eupelagic clay cores, such as core 51, all diatoms and nearly all radiolaria are practically completely peptized already below the top half meter stratum of the deposit (pl. 2.51, col. Radiolaria). In very old strata such as in core 53, (§ 2.53.12) the deposit has attained a vertically oriented, slaty fabric and neither the salinity, nor the water content[1]) indicate that the high strength (average $H = 200$) is connected to expulsion of water. These conditions indicate that the normal induration is due to ageing of the minerogenous and biogenous colloids and microcrystalline matter, which might slowly approach crystalline conditions.

The other diagenetical type, here called abnormally discontinuous induration, is found above all in the East Pacific Ridge sequences. Very good examples are cores 41 and 42, and further 44, 45, 47, and 48. Laminae and strata occur, which are cemented by silica to such an extent that the strength cannot be measured by the method adopted in the present work.[1]) In core 42 the process of silicification appears to go on at the present sediment surface. The facts that the radiolaria are not completely peptized and that the original concentration of siliceous skeletal structures in the petrified laminae and strata is not believed to be high enough to form compact chert, make it probable that much of the silica giving rise to this has migrated through the sediment. Except in the Galapagos area the diatoms are almost entirely peptized and the radiolaria are strongly corroded in the East Pacific Ridge sediments. The silica sol originating from the corrosion is believed to have migrated and to have been concentrated in strata where the physicochemical conditions favour precipitation. The question arises, why rapid peptization of diatoms and radiolaria and subsequent migration does not occur in the eupelagic calcareous sediments. Two probable explanations exist; one that the mobilization of the silica is dependent on a high content of organic matter in the sediment and therefore restricted to the East Pacific Ridge deposits, and the other that it is favoured by rising juvenile solutions or by rising interstitial water, heated at lower levels. The fact that the East Pacific Ridge is a center of volcanism would explain why the phenomenon in question is restricted to this area. Core 39, which has the highest content of organic matter in the East Pacific material does not display any marked corrosion of the diatoms and radiolaria. This is believed to favour the second of the alternatives mentioned. If juvenile solutions were active, hydrothermal mineralization might be expected. Thus REVELLE and EMERY (1951) have

[1]) In the case of this core the water content was checked after more than one year's storage and is therefore not very accurate. As the cores were stored in saturated water vapour, it is, however, believed that no great changes have taken place.

[1]) For a survey of the diagenesis of siliceous structures, s. CORRENS in BARTH, CORRENS and ESKOLA (1939, p. 250—253).

suggested that the barite nodules occuring off the coast of Southern California are most probably laid down by hot springs. Spectrochemical investigation of samples from cores 41 and 42, and from eupelagic calcareous oozes (cores 60 and 61) did, however, not reveal any great differences with regard to the concentration of heavy metals. The latter form of the second alternative might therefore be the most probable one in this case. The explanation is only tentative.

From a stratigraphical point of view the strength measurements are of great value, viz. for the indication of unconformities and surfaces of non-deposition. In cores 53 and 57, e. g., the strength at the top of the column is appr. three times the normal value and there is no sign of cementation with silica. A closer petrological and paleontological investigation demonstrates that these column tops are surfaces of non-deposition or erosion and that the outcrop is of Tertiary age (ch. 2.53, 2.57). The unconformity found in core 56 (ch. 2.56) is likewise clearly indicated by a corresponding discontinuity of the strength (pl. 2.56, col. $100 \cdot \log H$).

1.12.5 Reworking.

Reworking of the sediment, apparently caused by mud eating animals, is a general rule in all normal pelagic sediments studied by the present author. The importance of this effect for the interpretation of pelagic stratigraphy was first indicated by Bramlette and Bradley (1940) in the cores raised by C. S. Piggot from the North Atlantic. Owing to the interchange between dark and light colours in Equatorial eupelagic sediments, the digging structures are easy to trace with the naked eye. Examples of such structures are shown in pl. 2.6.1—2.6.10 and referred to in ch. 1.6. Several different kinds of traces of bottom scavengers are found, plough structures, pits, worm channels and cavities, sometimes containing faecal pellets. Through the activity of the mud-eating animals, all originally sharp boundaries have been diffused and the sediment has attained a brecciated structure, more or less obvious depending on the darkness and colour contrasts of the original strata. The greatest concentration of digging structures has been found in core 46 from the East Pacific Ridge, but owing to the dark manganese coloration of the sediment the structures are not as easily recognized in the photographs from this core as in those e. g. from core 61, where they are enhanced by the pure white colour of the chalk ooze.

The occurrence of digging structures, more or less visible, may thus be taken as a characteristic of normal pelagic deposits. The lack of such structures indicates abnormal conditions, probably a very high rate of deposition. The occurrence of sharp boundaries in pelagic sediments appears likewise to be an abnormal feature, indicating either a very high rate of deposition (as e. g. in sediment cores from the Romanche Deep in the Atlantic Ocean) or secondary precipitation from solutions migrating within the sediment (e. g. chert laminae in core 41 and manganese micro-laminae in core 61) or possibly a sterile bottom (euxinic environment).

Mixing, brought about by the bottom scavengers, appears to affect a layer 2—4 cm thick. Furrows and pits seldom exceed 1.5—2 cm in depth, whereas worm holes penetrate deeper, generally 2—4 cm. Worm holes exceeding 5 cm are very rare, but in one case a vertical (filled) channel was found, extending 25 cm down into the sediment (§ 2.46.6). 3 cm might be taken as a kind of standard deviation of reworking.

The stratigraphical uncertainty arising from reworking generally corresponds to time-rock units smaller than substages. A subdivision of these or a sampling of levels closer than 2—3 cm has thus generally no stratigraphical sense. Substages are generally

not affected by reworking except when the rate of accumulation is very low (e.g. in core 58), and the defining of stages is in no case believed to be influenced by reworking.

1.12.6. Recrystallization and chemical redistribution after deposition.

Chemical redistribution of several different types occurs. The one of greatest importance with regard to mass transport is associated with migrating solutions in the East Pacific Ridge sediments. The transport and precipitation of silica and the possible origin of the dissolution phenomenon has been treated in § 1.12.4. Associated with the migration of silica, redistribution of iron, manganese and phosphorus also appears to occur, and probably also of other elements. Thus the sequence in core 41 indicates that manganese and phosphorus have been leached from the lower beds and have been reprecipitated in the upper beds. This phenomenon appears to be restricted to the East Pacific Ridge and causes the high average manganese content in the calcareous surface deposits of this area, which is in contrast to the conditions found in the East Eupelagic area, where the average manganese concentration appears to be low, also in clayey sediments and where this element is believed to be practically entirely of halmyrogenous origin (s. § 1.5.3). High contents are also found in other centers of recent or extinct volcanic activity outside the area investigated here, viz. in parts of the Central Archipelagic area (fig. 1.0). Although the results of the analysis of manganese will not be treated in connection with the present work, the general outlines of the interpretation of the manganese distribution found might be briefly indicated. The origin of the manganese in deep sea sediments has been a matter of controversy (literature in Pettersson 1945 and Sverdrup e. a. 1946). The present results appear to indicate that both of the two main alternatives suggested by different authors to explain the content of manganese in pelagic surface deposits, are correct. Firstly, of the oxidates brought to the sea in the sol state, the manganese oxidates are largely deposited in the pelagic environment, whereas much of the iron oxidates are precipitated on the shelf (Rankama and Sahama, 1950). The manganese precipitated from sea water is here designated as halmyrogenous. The contribution of halmyrogenous manganese to the total manganese found in pelagic deposits has been stressed a. o. by Renard in Murray and Renard (1891) and by Kuenen (1941). Deposits of entirely halmyrogenous manganese are represented by the manganese oxide which coats solids in contact with sea water in environments free from minerolytic manganese (see below). Most of the manganese found in eupelagic deposits is believed to be halmyrogenous. The other source of this element in pelagic deposits is decaying minerogenous matter, e. g. volcanic debris. This source, which is here called the minerolytic one, was originally indicated by Murray and Renard (o. c.). The conditions found a. o. in core 41 indicate that selective diffusion and precipitation is the most probable explanation of the separation of minerolytic iron and manganese, resulting in the enrichment of minerolytic manganese in the surface strata of the sediments. This explanation has already been suggested by Murray and Renard (o. c.). Juvenile solutions or heated interstitial water might contribute to the transport and separation of iron and manganese, as was suggested by Gümbel (1878).

Another form of chemical redistribution is the short-distance transport which is believed to be brought about in connection with the decay of organic remains in oxidized sediments. References to reduction structures arising from this have been given in § 2.39.6—2.62.6 and are further treated in ch. 1.6. The diagenetical process includes in these cases the reduction of iron and especially manganese

compounds, which subsequently appear to have diffused out from the zone of reduction and to have been reprecipitated in the surrounding oxidized sediment. As a result a body of whitish sediment arises, embedded in a dark brown deposit. Phosphorus does not always appear to be mobilized in this type of reaction. An illustrative case is discussed in § 2.45.6.

An important form of secondary redistribution is associated with transformation of such matter which is unstable in the bathyal environment. The decomposition of organic matter has been treated in ch. 1.4 and the redistribution of silica, dissolved from radiolaria and diatoms, and of compounds originating from minerolysis, has been referred to in the preceding paragraphs and in the earlier parts of this one. It should be mentioned in addition that the diatoms appear to be most sensitive to peptization, followed by small sized radiolaria. Big sized radiolaria and especially sponge spicules are more resistant but are still in many cases found to be nearly completely dissolved. Calcium carbonate appears to reduce the intensity of peptization. The result of all these effects can be traced in the regional and stratigraphical distribution of siliceous remains. The East Eupelagic calcareous deposits are generally rich in diatoms and radiolaria in a perfect state of preservation, whereas corresponding time-rock units in the East Pacific Ridge are free from diatoms or contain only small amounts of extensively corroded frustules and are very poor in radiolaria in spite of the indications of a higher production of siliceous organisms in the latter area than in the former. Much of the corrosion of the siliceous remains appears to be prehume, as the rate of corrosion appears to vary with the rate of accumulation. As mentioned above, the small-sized radiolaria appear to be more readily peptized than the big ones. As a result, an investigation of the size distribution of *Cyrtoidea* revealed an enrichment of big sized specimens in strata deposited with a low rate of accumulation. The increased corrosion might possibly also be explained by the lowered concentration of calcium carbonate normally associated with a low rate of accumulation.

In the pelagic clays of the East Pacific the corrosion is very far-reaching and apparently also posthume, as the concentration of uncorroded skeletons decreases gradually downwards in the deposit in several cases. As several clays of the Central Pacific are known to be rich in apparently uncorroded radiolaria, the conditions determining the dissolution of siliceous structures must be regarded as not quite clear.[1])

Recrystallization of foraminiferal tests is very frequent in the East Pacific sediments. This phenomenon was first reported by Murray and Philippi (1908) and was further studied in the Pacific sediments by Revelle (o. c.). Revelle observed that a high percentage of recrystallized tests is usually restricted to sediments of intermediate carbonate content, with a high percentage of broken planktonic tests and relatively rich in benthonic forms. This is confirmed by the present results which demonstrate that the conditions mentioned by Revelle are typical of environments with a low rate of biogenous accumulation. Recrystallized tests were, however, found also in strata rich in calcium carbonate and with a high rate of accumulation. Further, the study of thin sections demonstrates that benthonic and recrystallized planktonic foraminifera are not as readily corroded as foraminifera, which are not recrystallized. The increased percentage of recrystallized foraminifera in sediments, deposited with a low rate of accumulation, may therefore be an effect of enrichment.

The dissolution of calcareous structures has been mentioned in ch. 1.1. Correns (o. c.) has pointed out that although the dissolution of calcium carbonate in the deep sea is a well

[1]) Measurements of the pH of all East Pacific samples immediately after the extraction of these did not reveal any principal differences between the East Eupelagic and the East Pacific Ridge sediments.

established fact, no observations of traces of corrosion in foraminifera have been reported. CORRENS concluded that the main part of the calcium carbonate dissolved was derived from small sized carbonate particles such as coccoliths and foraminiferal fragments, these having an increased solubility and a great surface per unit mass. This interpretation is confirmed by the present results as far as chalk oozes are concerned but necessitates the assumption that the strongly lowered concentrations of foraminifera in the pelagic marl oozes and clays is entirely due to a decreased production. In the beginning of the present study no evidence was found of corrosion of foraminifera, which led the present author to accept the assumption mentioned above (ARRHENIUS, 1950). Fragmentation of the tests was found to be common but the fragments did not appear corroded, when studied in reflected light except in the strongly altered sediments from the East Pacific Ridge. Finally, however, it was revealed that thin sections of the tests permit a much more successful study of corrosion than do observations in reflected light at the enlargements usually applied in the routine study of foraminifera (up to 100 ×). Studies of thin sections of washed foraminifera mounted in polymethyl metacrylate[1]) revealed the fact mentioned above, viz. that planktonic foraminifera, which are not recrystallized are more easily attacked than recrystallized specimens and than benthonic foraminifera, which appear to be remarkably resistant to dissolution. Further, experiments were made with dissolution of tests of *Globorotalia menardii-tumida* in carbonic acid. Although the concentration of the acid was taken higher than under natural conditions so that complete dissolution of the tests was attained within a few weeks, the results might be of value for the interpretation of the conditions found in the sediments. From the experiments mentioned it was obvious that the visible corrosion proceeded first slowly but later at an increased speed. Further, dissolution proceeding laterally appeared to be more frequent than thinning of the tests. These two facts may explain why the last remains of thinned tests, where the action of dissolution is perceptible also at small enlargements and in reflected light, are very seldom found in nature. The corrosion study is continued on a quantitative basis and the results will appear elsewhere. — CORRENS (o. c.) indicated that the organic matter, which binds together the calcite prisms of the foraminiferal tests, might possibly be dissolved in the intestinal tracts of bottom scavengers, the tests thus being disintegrated to minute calcite plates. Decomposition of this kind was attained by CORRENS through boiling foraminiferal tests in 10 % KOH. The present author tried to attain the same effect by treatment with a peptolytic enzyme (papain) but with no success. This may indicate a keratinoid rather than an albuminoid binder.

1.12.7 Water content — pressure relations.

The studies of the East Pacific sediments have not yielded any quantitative results with regard to the influence of the thickness of the overlying sediment on the water content of a stratum. The reason is that in the sediments investigated, this effect appears to be so small as far as the upper 10 m layer is concerned, that it is usually masked by the variations in composition of the deposit. The effects of this on the water content have been referred to in § 1.12.2. In core 51 the salinity of the lower beds indicate a slight expulsion of water (§ 2.51.12) but there is a very poor quantitative correlation between salinity and depth also in this core. Other clay cores, too, display a decreased salinity in the lower beds (e. g. 48 and 55) but it is not possible to prove whether this effect is due to pressure, to ageing or to the deviating composition of the sediment (high content of manganese oxides in the phosphatic strata). In calcareous facies of

[1]) According to a method by HAGERMAN (unpubl.)

the East Eupelagic area, even the longest core (no. 62, 15 m long) does not give any unquestionable evidence of expulsion of water due to pressure. The hydration equilibrium appears generally to have been established in a shorter time than a few thousand years and thus to be attained already in the top few centimeters of the cores. The possible modifications caused by increased pressure in lower levels might be recognized and studied when the exact relationships between composition and hydration equilibrium are known.

References

Arrhenius, G. 1949. Svenska Djuphavsexpeditionens geologiska material och planerna för dess bearbetning. — Geol. Fören. Stockholm Förhandl. *71*, p. 191—201.

— — 1950. Late Cenozoic climatic changes as recorded by the Equatorial Current System. — Tellus, *2* p. 83 and 236.

Arrhenius, G., Kjellberg, G. and Libby, W. F. 1951. Age determination of Pacific chalk ooze by radiocarbon and titanium content. — Tellus *3*, p. 222—229.

Arrhenius, G. and Blomqvist, N. 1953. Estimation of lutite and biogenous silica in eupelagic sediments. — Rep. Swed. Deep-Sea Exp. *5*, part *5* (in preparation).

Barth, T., Correns, C. and Eskola, P. 1939. Die Entstehung der Gesteine. — Bln.

Bouma, P. J. 1947. Physical aspects of colour. — Eindhoven.

Bramlette, M. N. and Bradley, W. H. 1940. Geology and biology of North Atlantic deep sea cores. — U. S. Geol. Survey, Prof. Paper 196 — A.

Chaney, R. W. 1940. Tertiary forests and continental history. — Bull. Geol. Soc. Am. *51*.

Clarke, F. W. 1924. The data of geochemistry, 5th ed. — U. S. Geol. Survey Bull. 770.

Conway, E. J. 1945. Mean losses of Na, Ca, etc. in one weathering cycle and potassium removal from the ocean. — Am. Jour. Sci. *243*, p. 583.

Correns, C. W. 1937. Die Sedimente des Äquatorialen Atlantischen Ozeans. — Wiss. Ergebn. d. Deutschen Atl. Exp. Meteor 1925—1927, *3*, 3.

Dietz, R. S., Emery, K. O. and Shepard, F. P. 1942. Phosphorite deposits on the sea floor off Southern California. — Geol. Soc. Am. Bull. *53*, p. 815.

Durham, W. 1951. Cenozoic marine climates. — Bull. Geol. Soc. Am. *62*, p. 1433—1434.

Emery, K. O. and Dietz, R. S. 1950. Submarine phosphorite deposits off California and Mexico. — Calif. Jour. Mines and Geol. *46*, p. 7—15.

Flint, R. F. 1947. Glacial geology and the Pleistocene epoch. — N. Y. & Ld.

Frederickson, A. F. 1948. Mode of occurrence of titanium and zirconium in laterites. — Am. Min. *33*, p. 374.

Fritsch, F. E. 1948. The structure and the reproduction of the algae. — Cambridge Univ. Press.

Geitler, L. 1932. Der Formwechsel der pennaten Diatoméen. — Arch. f. Protistenkunde, *78*.

Goldschmidt, V. M. 1922. Der Stoffwechsel der Erde. — Videnskabsselskabets Skrifter I. Matem.-Naturvet. Klasse, no. 11.

Graham, H. W. 1941. Plankton production in relation to character of water in the open Pacific. — Jour. Marine Research, *4*, p. 189.

v. Gümbel, G. 1878. Sitz. Ber. Bayr. Akad. d. Wiss. *2*, p. 189.

Iyengar M. O. P. and Subrahmanyan, R. 1944. On reduction division and auxospore-formation in Cyclotella Meneghiniana Kütz. — Jour. Ind. Bot. Soc. *23*, p. 125—152.

Koczy, F. 1950. Zur Sedimentation und Geochemie im Äquatorialen Atlantischen Ozean. — Medd. Oc. Inst. Göteborg, 17.

— — 1951. Factors determining the element concentration in sediments. — Geochimica et Cosmochimica Acta, *1*, p. 73—85.

Krumbein, W. C. and Garrels, R. M. 1952. Origin and classification of chemical sediments in terms of pH and oxidation-reduction potentials. — J. Geol. *60*, p. 1—33.

Kuenen, Ph. H. 1941. Geochemical calculations concerning the total mass of sediments in the earth. — Am. Jour. Sci. *39*, p. 161.

— — 1950. Marine geology. — Ld. & N. Y.

Marshall, C. E. 1949. The colloid chemistry of the silicate minerals. — N. Y.

Murray, J. and Renard, A. 1891. Deep-sea deposits. — Rep. Sci. Res. Challenger.

Murray, J. and Philippi, E. 1908. Die Grundproben der Deutschen Tiefsee-Expedition. — Wiss. Ergebn. d. Deutschen. Tiefsee-Exp. Valdivia *10*, p. 77—206.

Ovey, C. D. 1948. Some ecological aspects of the foraminifera and their application to stratigraphy. — South-Eastern Naturalist and Antiquary *53*, p. 39—47.

Persidsky, B. M. 1929. The development of the auxospores in the group of the Centricae (Bacillariaceae). — Moscow.

Pettersson, H. 1945. Iron and manganese on the ocean floor. — Medd. Oc. Inst. Göteborg, 7.

Pettijohn, F. J. 1949. Sedimentary Rocks. — Ld and N. Y.

Phleger, F. B. 1951. Ecology of foraminifera, Northwest Gulf of Mexico. — Geol. Soc. Am. Mem. *46*.

Rankama, K. and Sahama, T. 1950. Geochemistry. — Chicago Univ. Press.

REVELLE, R. and SHEPARD, F. 1939. Sediments off the California coast. — p. 245—282 in TRASK (ed.) 1939.

REVELLE, R. 1944. Marine bottom samples collected in the Pacific Ocean by the Carnegie on its seventh cruise. — Carnegie Inst. Wash. Publ. 556.

REVELLE, R. and EMERY, K. 1951. Barite concretions from the ocean floor. — Bull. Geol. Soc. Am. *62*, p. 707—724.

SCHOTT, G. 1935. Geographie des Indischen und Stillen Ozeans. — Hamburg.

SCHOTT, W. 1935. Die Foraminiferen in dem Äquatorialen Teil des Atlantischen Ozeans. — Wiss. Ergebn. d. Deutschen Atl. Exp. Meteor, 1925—1927 *3*, 3.1.A.

SELLING, O. H. 1948. On the Late Quaternary history of the Hawaiian vegetation. — B. P. Bishop Museum Spec. Publ. 39. Honolulu (Göteborg).

SVERDRUP, H. U., JOHNSON, M. W. and FLEMING, R. H. 1946. The Oceans. — N. Y.

TRASK, P. D. 1939. Organic content of recent marine sediments. — Recent Marine Sediments. Am. Ass. Petrol. Geol., Tulsa.

UMBGROVE, J. H. F. 1947. The pulse of the Earth. — The Hague.

WAKSMAN, S. A. 1933. On the distribution of organic matter in the sea bottom and the chemical nature and origin of marine humus. — Soil Sci. *36*, p. 125—147.

WEIBULL, W. 1949. — A statistical analysis of the size of Cyrtoidea in Albatross cores from the East Pacific Ocean. — Nature *164*, p. 1047.

WIEDLING, S. 1948. Beiträge zur Kenntnis der vegetativen Vermehrung der Diatomeen. — Botaniska Notiser.

WILLETT, H. C. 1949. Solar variability as a factor in the fluctuations of climate during geological time. — Geogr. Annaler, p. 295—315.

WISEMAN, J. D. and BENNETT, H. 1940. The distribution of organic carbon and nitrogen in sediments from the Arabian Sea. — Sci. Rep. John Murray Exp. 1933—1934, *3*, p. 193—221.

WISEMAN, J. D. and OVEY, C. D. 1950. Recent investigations on the deep sea floor. — Proc. Geol. Ass. *61*, 1 p. 28—64.

ZEUNER, F. E. 1945. The Pleistocene period. — Ray Soc, *130*.

REPORTS OF THE SWEDISH DEEP-SEA EXPEDITION. VOL. V
SEDIMENT CORES FROM THE EAST PACIFIC

PART 2

DESCRIPTION OF THE SEDIMENT CORES

BY

GUSTAF ARRHENIUS

Core 38

East Pacific Ridge

(Galapagos area)

Station no. 52.

Lat. 2° 52′ S, *Long.* 89° 50′ W.

Depth 3 225 m.

Length of core 405 cm.

Topography: Regular bottom (fig. 2.38.0).

Abstract of interpretation. Core 38 consists of a poorly stratified chalk ooze, rich in organic matter. The rate of sedimentation is supposed to be of the order of magnitude 4 cm/1 000 years. The high rate of deposition appears to be due partly to the high local production of biogenous material at the surface of the ocean, partly to a comparatively high rate of minerogenous sedimentation. The minerogenous matter is poor in iron, manganese and phosphorus and is believed to a large extent to be derived from the Galapagos plateau. It has not been possible to correlate core 38 with other cores.

.1 Calcium carbonate. As is evident from the stratigraphical diagram (pl. 2.38) the calcium carbonate content is high and abnormally constant through the whole column with only a slight decrease downwards. The number of foraminifera per weight unit of calcium carbonate is abnormally high (fig. 2.38.7.1), indicating a high rate of accumulation.

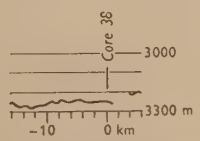

Fig. 2.38.0. Bottom topography in the vicinity of the station of core 38. Redrawn from Koczy (contribution to vol. IV).

.4 Organic matter. Both carbon and nitrogen are evenly distributed. The concentrations are high, which appears to be the normal case in the easternmost part of the Equatorial Pacific. The correlation between carbon and nitrogen concentrations (fig. 2.38—39.4) is close to the average equation for East Equatorial chalk and marl oozes.

.5 Phosphorus. The concentration of phosphorus is appr. 2.5 times lower than in eupelagic deposits with the same carbonate content as core 38 (fig. 2.38—39.5). This might partly be due to admixture of terrigenous matter from the Galapagos plateau as appears to be the case also in core 39 on the southwestern and in core 40 on the northern side of this plateau.

As is seen from table 2.38.5 the Galapagos lavas are fairly low in phosphorus and during weathering the concentrations are still more

TABLE 2.38.5

	$P_2O_5 \cdot 10^4$	$Fe \cdot 10^2$
Andesitic lava, James Island, Galapagos	15	12
Andesitic lava, Chatham Island, Galapagos	23	13
Tuff, strongly weathered, James Island, Galapagos	5	8
core 38 average in carbonate free matter	14	0.9
core 39 average in carbonate free matter	7	0.6
core 40 average in carbonate free matter	9	0.5

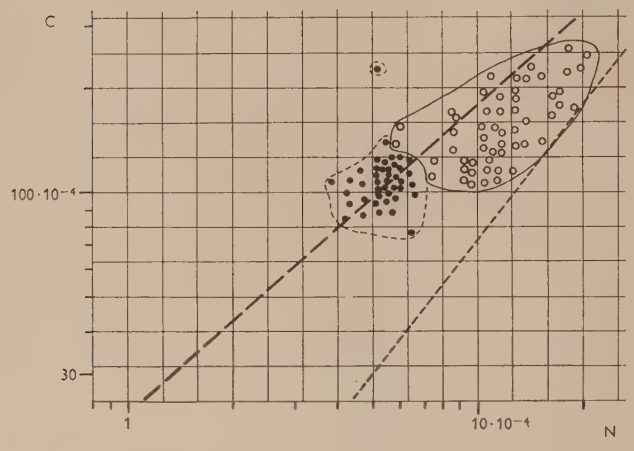

Fig. 2.38—39.4. Relation between carbon and nitrogen concentrations in core 38 (filled circles) and 39 (open circles). The heavy dashed line corresponds to the estimated average of the calcareous East Pacific deposits and the light dashed line illustrates the equation indicated by ARRHENIUS 1950.

decreased, partly through dissolution of phosphates, partly through hydration of the silicates. The phosphate content of the weathered tuff investigated is thus lower than the average contents of core 38 and 40 calculated on carbonate free matter. This might be due to the effect mentioned in ch 1.5, namely that the iron and (or) manganese compounds of a deposit surface in contact with sea water appear to react with the dissolved phosphates and precipitate them as iron and (or) manganese phosphates thus slowly increasing the phosphorus concentration of the surface layer of the sediment. The low concentration of phosphorus in the cores collected around the Galapagos plateau might thus be explained by three different factors, viz. 1) The low phosphorus concentration of the source material, 2) the low iron and manganese content of the sediment and perhaps also other properties decreasing the rate of adsorption-precipitation and 3) a comparatively high rate of accumulation, the two latter factors counteracting the adsorption of phosphorus after deposition.

The layer 320—220 cm is characterized by an increased concentration of phosphorus both in the bulk and in that part of the sediment which is free from calcium carbonate. No corresponding increase in the iron content can be traced and the calcium carbonate content indicates only a slight increase in the rate of terrigenous sedimentation (or decrease in biogenous calcium carbonate sedimentation, or both). The reason for the higher phosphorus content is therefore believed mainly to be an increased content of this element in the source material.

.6 Colour and pattern. The colour of core 38 is very regularly distributed, the lower half being yellowish-greenish grey (1 ge—ec) with a continuous transition to yellowish grey (2 ge—ec) of the same shade in the upper half of the column.

A remarkable structure which has not been found in any of the other cores investigated consists of irregular bodies having the approximate shape of concentric cylinder mantles, the

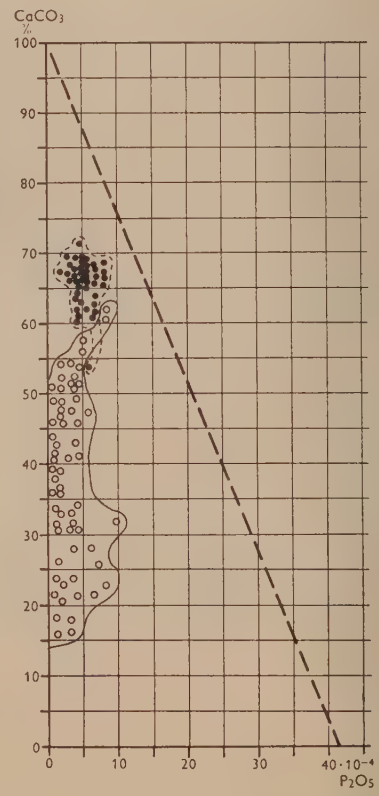

Fig. 2.38—39.5. Relation between concentration of phosphorus and concentration of calcium carbonate in core 38 (filled circles) and core 39 (open circles). The dashed line corresponds to the estimated eupelagic average.

axis coinciding with that of the sediment core. The colour of these bodies (*2ec, 2ig—li*) differs with one or two shades from that of the ground mass. These structures present similarities to secondary changes of reduced shelf sediments at oxidation after core sampling. It is believed that the mantle structures of core 38 too are of secondary origin and formed during the storage on board probably through oxidation starting at the surface of the core sections. Pl. 2.6.1 shows sections of the mantles. The core is very poor in the typical reworking pattern caused by mud-eating animals and found in almost all oxidized and slowly deposited pelagic sediments.

As in the cores 39 and 41 the topmost few centimeters are darker (5pl—2ig) than the underlying sediment (2ge—ec) and richer in carbon and nitrogen. The lower boundary of this topsoil is irregular and fairly sharp.

.7 Foraminifera. Two conspicuous maxima in the concentration of foraminifera occur; one at 210 and one at 390 cm. Their significance is obscure as there is no corresponding increase in the percentage of calcium carbonate and no conspicuous decrease in the concentration of fragments of foraminifera. The percentage of benthonic foraminifera is low with regard to the number of plankton (fig. 2.38—39.7.2). As in the other cores belonging to the Galapagos group, the fauna is dominated by the genus *Globigerina*. *Globorotalia* does not exceed 10 %, *Orbulina universa* is comparatively well represented. *Sphaeroidinella dehiscens* and *Sphaeroidina bulloides* are absent. The changes of the faunal composition in core 38 are not very marked and their significance is obscure.

.8 Radiolaria. The concentration of radiolaria is low with regard to the percentage of calcium carbonate and compared to the concentrations in the corresponding lithofacies in the Central Equatorial Pacific. Marked changes in the average concentration occur, but it has not been regarded

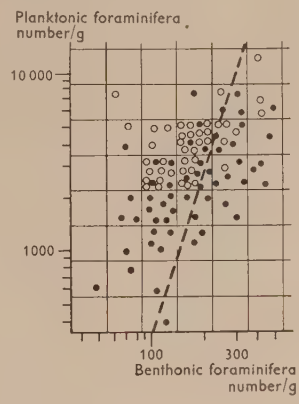

Fig. 2.38—39.7.2. Relation between concentration of entire tests of planktonic and benthonic foraminifera in cores 38 (open circles) and 39 (filled circles). The dashed line corresponds to the estimated eupelagic regression (§ 1.7.2.).

In core 38 the concentration of benthos is abnormally low, which is believed to indicate that the rate of deposition is high. This results in a low rate of dissolution of calcium carbonate and in retardation of the normal enrichment of resistant benthonic forms.

In core 39 the regression is less steep than the eupelagic average. This is believed to confirm the assumption that in core 39 the changes in foraminiferal concentration are to a higher degree than in the eupelagic environment connected to changes in the rate of accumulation of foraminifera and in a smaller degree to changes in the fragmentation (cf. § 1.7.2). This is ultimately regarded as an effect of the high rate of accumulation in the Galapagos area.

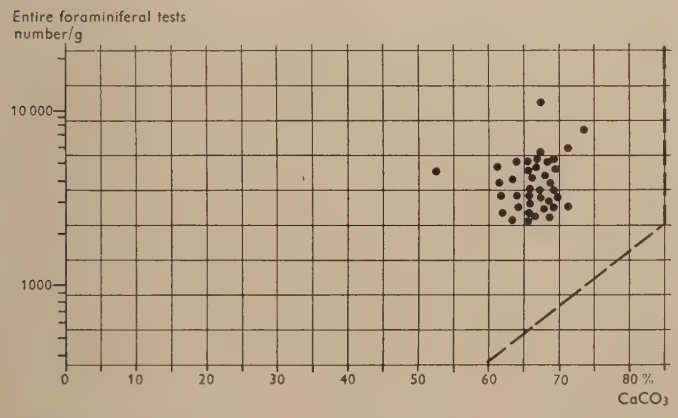

Fig. 2.38.7.1. Relation between concentration of entire foraminiferal tests and percentage of calcium carbonate. The dashed line illustrates the average eupelagic conditions.

The high number of entire tests per unit weight of carbonate indicates a high rate of accumulation, preventing fragmentation of the tests. The comparatively low mean diameter of the tests (high percentage of *Globigerina* species) also contributes to the distribution found.

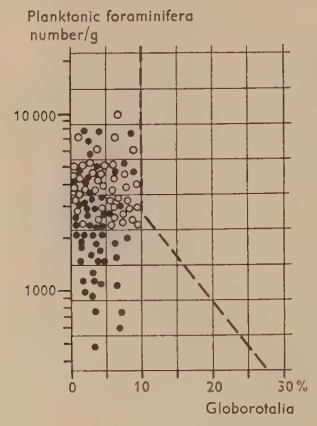

Fig. 2.38—39.7.3. Relation between concentration of entire tests of planktonic foraminifera and planktonic faunal percentage of *Globorotalia menardii + tumida*. The guide line coincides roughly with the eupelagic equiprobability curve 0.05, i. e. the probability of occurence of a sample outside this boundary is less than 5 percent.

The ecological conditions in the Galapagos area, presumably mainly the low temperature of the surface water, prevent extensive development of *Globorotalia menardii + tumida* and even when the rate of production (upwelling) attains minimum, the fauna is dominated by *Globigerina* species. Dr. Brotzen has directed the author's attention to the fact that many of the small *Globigerina* forms which dominate the assemblages in this area may be specimens of *Orbulina universa* the outer shells of which have been destroyed by crushing and dissolution.

possible in this case to draw any stratigraphical conclusions from the variations.

.9 Diatoms. The size distribution of *Coscinodiscus nodulifer* was investigated (pl 2.38) and found to be very regular through the entire column. Secondary maxima of big forms are missing.

.12 Diagenesis. A slight increase in the strength characterizes the uppermost 270 cm. This increase corresponds to the slightly raised percentage of calcium carbonate. In the correlation diagram $CaCO_3$—Salinity the samples from core 38 are located close to the left boundary line (fig. 2.38—39.12) i. e. the salinity is below normal. The reason for this might be a low content of colloidal silica. There are only few traces of mud-eater activity, which is in agreement with the low percentage of benthonic foraminifera and other signs of a high rate of sedimentation.

.13 Stratigraphy. The great homogeneity and lack of conspicuous stratification makes it difficult to subdivide core 38 and correlate it with other cores. In the neighbouring core 39 the zone C 4 is found at appr. —320 cm. With regard to the higher percentage of calcium carbonate in core 38 this zone should be found at 430—450 cm at the locality 38, provided the rate of minerogenous accumulation were the same as in core 39. Under such circumstances core 38 which is only 4 meters long cannot be expected to penetrate deep enough to record the production minimum 3.

The lack of stratification in core 38 might be explained by assuming that the rate of upwelling in this area has never decreased enough to make the supply of plant nutrients a limiting factor during the deposition of the beds sampled. This explanation is made probable by the conditions found in core 61 below the Equatorial divergence further to the west. This core, like core 38, records a high productivity subjected to considerably smaller changes with time than in the cores 59 and 60 further to the north. On account of the lower rate of upwelling in comparison with the locality 38 the stratification due to pro-

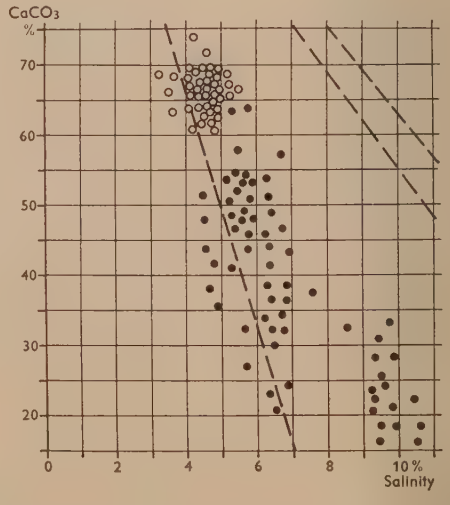

Fig. 2.38—39.12. Relation between calcium carbonate content and salinity in core 38 (open circles) and 39 (filled circles). The dashed lines correspond to lines A, B, and C in fig. 1.12.2.1 and 1.12.2.2.

duction changes is, however, still traceable in core 61.

The size distribution of *Coscinodiscus nodulifer* in core 38, however, appears to contradict the explanation suggested above, as the frequency maximum of large sized specimens, normally connected to a very high rate of production, is lacking throughout core 38. The stratigraphy of this core cannot, therefore, be regarded as fully explained.

Core 39

East Pacific Ridge
(Galapagos area)

Station no. 55.
Lat. 2° 44′ S, *Long.* 92° 45′ W.
Depth 3 600 m.
Length of core 528 cm.

Topography: Regular bottom except a group of sea mounts of approx. 100 m elevation appr. 9 and 12 km east of the station (fig. 2.39.0).

Abstract of interpretation. The sequence consists of marl ooze coloured dark by organic matter alternating with clay and a thin layer of chalk ooze in the upper marl bed. The top of the existing core is characterized by a decreasing carbonate content. The real top 10—20 cm layer is supposed to be lost due to the coring technique. The lowest marl ooze stratum is believed to correspond to the upper part of stage 6, the intermediate marl stratum to stage 4. The upper marl ooze with chalk stratum includes stage 2 and the lower parts of stage 1. Recent and Subrecent (upper part of stage 1) correspond to the missing top layer. The lower and upper clay beds correspond to the stages 5 and 3. The substage 3.2 is represented by the marl- clay stratum at 260—250 cm. Other detail features of the general eupelagic stratigraphy are obscured by variations in the rate of sedimentation of minerogenous matter which is believed largely to be derived from the Galapagos plateau. This terrigenous matter has a high content of organic matter. The final concentrations of carbon and nitrogen in the deposit are influenced by decomposition which appears to have been more intense when the rate of accumulation was low.

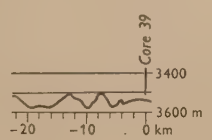

Fig. 2.39.0. Bottom topography in the vicinity of the station of core 39. Redrawn from Koczy (contribution to vol IV).

The rate of calcium carbonate accumulation is lower than in core 59 but greater than in core 58.

The average rate of minerogenous accumulation since the time corresponding to the level C 4 is appr. seven times higher (appr. 530 fors[1]) than in the eupelagic environment.

.1 Calcium carbonate. The percentage of calcium carbonate is subject to very marked changes in core 39, and ranges from 17 to 65. The minor variations appear to be due to changes in the minerogenous sedimentation (cf § 2.39.4) whereas the major features appear to be caused by the general Equatorial Pacific productivity changes and therefore usable for correlation purposes (cf § 2.39.13). The amount accumulated since the time corresponding to the level C 4 is appr. 46 g/cm², i. e. less than in core 59 but more than in core 58.

.4 Organic matter. Core 39 contains the richest sapropel deposits found in the material collected from the Pacific with the exception of cores 35 and 36 from the Gulf of Panama (not included in this treatise). The maximum values in core 39 amount to 2.5 % carbon and 0.2 % nitrogen. As is seen from fig. 2.38—39.4 the ratio C/N is remarkably low with regard to the high carbon and nitrogen concentrations. In this respect the organic matter of core 39 approaches the carbon-nitrogen relationship of lacustrine deposits and shelf sediments (Arrhenius 1950), which is indicated with a thin dashed line in fig. 2.38—39.4.

[1]) 1 for = 1 mg/cm² · 1000 years.

There is a marked stratification in core 39 with regard to organic matter, the upper and lower marl beds being richer and the intercalated clay poorer in carbon and nitrogen. The main features of the carbon curve, recalculated for carbonate-free material are conformous with the calcium carbonate curve as is seen from the curves $CaCO_3$ and C: $(1-CaCO_3)$ in pl. 2.39. From the curve C: $CaCO_3$ it is evident, however, that the amount of organic matter per unit weight of calcium carbonate is subject to strong variations and further that this amount is greatest when the calcium carbonate content is lowest and vice versa.

These conditions indicate that at least two independent factors influence the concentration of organic matter in core 39, one tending to decrease this concentration when the carbonate concentration is decreased, the other raising the amount of organic matter under the same circumstances. Generally speaking the first factor can be said mainly to control the gross features of the distribution of organic matter and to cause a minimum in the curve C: $(1-CaCO_3)$ at approx. 280 cm. The second factor appears to dominate the subordinate periodicity of the concentration of organic matter as a function of the depth in the sediment. This second factor is believed to be the changing rate of deposition of organic matter. This is apparently not directly connected to the rate of deposition of minerogenous matter as the quotient C: $(1-CaCO_3)$ is not constant but is often strongly increased together with the factor $(1-CaCO_3)$.

The deposition of organic matter thus appears to have varied considerably but definitely not dependent upon or in the same way as the deposition of carbonates. Nor does it appear to have varied in direct proportion to the minerogenous component, but is apparently connected to this latter factor for some reason which can at the present moment only be guessed at. The effect of dilution with calcium carbonate is obviously not a sufficient explanation. Probably the changes in deposition of organic matter depended on changes in the rate of influx of material from shallow water deposits rich in organic matter. Such sediments, originally deposited on the Galapagos plateau might have been brought into suspension by wave action in connection with the lowered sea level during the ice ages (stages 2 and 4).

Secondary decomposition of organic matter at or close to the sediment surface is believed to constitute the first mentioned factor, which tends to decrease the carbon and nitrogen content of the minerogenous matter in the clayey strata and thus to counteract the second factor. The clay strata represent ages of strongly decreased total rate of accumulation under the condition that the rate of minerogenous sedimentation has not been markedly increased. Such an increase is usually easy to trace in the structure of the sediment in the neighbourhood of islands (appearance of considerable amounts of silt and sand, greater scarcity of mud-eater traces etc.) but there is no such evidence in core 39. The organic matter deposited on the clay surfaces therefore belonged during a considerable length of time to the topsoil of the sediment until this was buried. It thus remained for a comparatively long time in contact with the oxidizing sea water, was extensively reworked by mud-eating animals, passed through their intestinal tracts, and was further attacked by bacteria, abundant in the surface layer of the sediment (Zo Bell and Andersson 1936). The most pronounced decrease in the amount of organic matter per unit weight of minerogenous matter (curve C: $[1-CaCO_3]$) is found in the stratum 317 cm to 231 cm representing the longest stage (= stage 3) recorded by core 39 with a comparatively low rate of accumulation interrupted only by the subordinate increase of calcium carbonate between 262 and 251 cm (= substage 3.2). There might be a general effect of ageing of the organic matter, superimposed on the variations caused by changes in

rate of deposition of organic matter and in the rate of secondary decomposition at the sediment surface or close to it. This presumed effect of ageing probably causes the general decrease of nitrogen and carbon concentrations with increasing depth in the sediment, but this could also be a primary feature.

.5 Phosphorus. The general conditions for the deposition of phosphorus in the Galapagos area have been treated in paragraph 2.38.5. In core 39 the average phosphorus concentration is still lower than in cores 38 and 40 (fig. 2.38—39.5). As is seen from the curve P_2O_5: ($1-CaCO_3$) (pl. 2.39) there are several marked changes in the amount of phosphorus per unit weight of non-calcareous matter. As in core 38 these probably have to be referred to changes in the composition of the minerogenous source material and in the reducing environment, but it is difficult to trace the cause of these changes without investigation of additional material from the Galapagos region.

.6 Colour and pattern. (pl 2.6.1 and pl 2.39). The ground mass of the sediment represented by core 39 is characterized by yellowish colours of one single hue (2) and of one single shade (c) except the layer 370—320 cm which has the shade e (colour 2 lg). The degree of blackness varies considerably as is seen from the diagram in pl 2.39. The greatest amount of black is found in the clay member 3 and in connection to the maxima of organic matter in the upper marl bed. The blackness appears in the first place to be caused by abundance of dark organic matter. On the whole core 39 is dark, the smallest degree of blackness being g.

Especially the layers of clay and clayey marl are rich in all sorts of mud-eater traces such as worm holes, lenticular furrows, cavities filled with loose mud and in one case with faecal pellets, layers of the type 40—873 x (see paragraph 2.40.6) etc. Special samples were extracted from such structures and analyzed.

The sample 39—37 x was extracted from layers and bodies with the colour 2 ec between the levels 37 and 70 cm and shows normal carbonate and phosphate content, a markedly lowered content of organic matter and a slightly lowered salinity.

39—145 x corresponds to a layer very rich in small holefillings and irregular bodies of a colour 2 nl and has the same properties as 39—37 x. Further it is looser than the surrounding sediment and slightly poorer in foraminifera.

39—237 x is derived from a greyish black (n) diffusely limited body which appears to be normal with regard to carbon and salinity but to have a slightly lowered carbonate content. The number of foraminifera is above and the number of fragments below normal. The iron content is normal. This body does not appear to be a digging structure and the coloration is probably due to precipitation of manganese or sulphides. A similar case is 39—358 x, in section appearing as a horseshoe shaped, dark band (5ni).

39—404 x and 39—412 x are made up of the loose, dark (2li) filling of rounded, oblong cavities, 3—5 cm long. Calcium carbonate and carbon are considerably decreased, whereas the nitrogen content is remarkably high in the case of 39—412 x. No material was left to check the amount of nitrogen decomposed to ammonium salts.

.7 Foraminifera. As appears from fig. 2.39.7.1 the number of intact foraminifera is as in core 38 abnormally high in core 39, this being due to the high rate of accumulation. As a consequence the quotient: entire tests-fragments is also high (approx. average 1.2 in the clay and 2.4 in the marl beds). As in core 38 the percentage of *Globorotalia* is extremely low (fig. 2.38—39.7.3) and the planktonic fauna is dominated by the genus *Globigerina*. *Sphaeroidina bulloides* and *Sphaeroidinella dehiscens* are absent and *Pulleniatina obliquiloculata* is scarce, whereas *Orbulina universa* reaches the highest percentages (6—

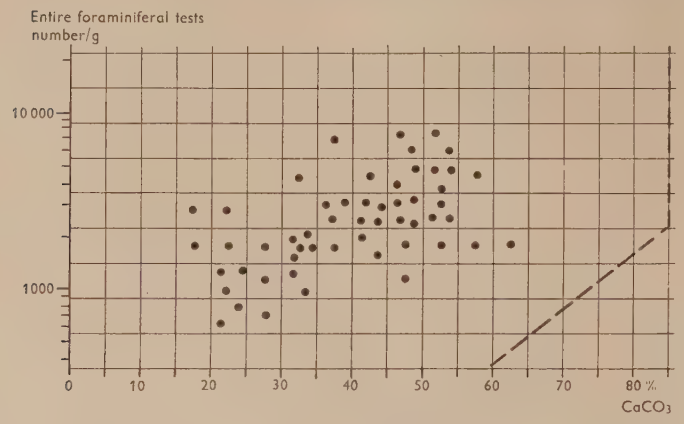

Fig. 2.39.7.1. Relation between concentration of entire foraminiferal tests and percentage of calcium carbonate. The dashed line illustrates the average eupelagic conditions.

The distribution features are the same as in core 38 (fig. 2.38.7.1). In the clay strata the concentration of entire tests is appr. 20 times the normal eupelagic concentration. This is due to the high minerogenous rac (appr. seven times the rac of eupelagic lutite) and to the high rate of production in the Galapagos area.

7 %) recorded in the undisturbed East Pacific sequences. The concentration of benthonic foraminifera tends to be higher than normal in samples rich in planktonic foraminifera and below normal in cases of low concentration of planktonic specimens (fig. 2.38—39.7.2). The percentage of benthos calculated on the basis of the number of planktonic specimens, varies between 2 and 21 % (pl. 2.39). The varying rate of minerogenous sedimentation in core 39 and possibly also other factors make it difficult to interpret the variations in distribution of benthos in this core.

.8 Radiolaria. The concentration of radiolaria is subject to strong and regular variations. The lower stages 6—4 are comparatively rich in radiolaria and the concentration decreases gradually upwards. A marked minimum occurs at 55 cm. The significance of these changes is not known.

.9 Diatoms. The typical size distribution of *Coscinodiscus nodulifer* in the East Eupelagic area is repeated in core 39 and confirms the stratigraphical conclusions based upon the calcium carbonate distribution in core 39. The level C4 is here located at 320 ± 10 cm. Core 39 is as a whole rich in diatoms and these are in a good state of preservation.

.11 Mineral grains and rock fragments. Grains $> 150\,\mu$ of volcanic glass occur in many samples of core 39. The frequency does not exceed a few per g sediment.

.12 Diagenesis. The lower marl bed has a shearing strength approx. 1.6 times higher than the upper one, which indicates secondary induration of the lower bed. Also the intercalated bed of clay and marl shows signs of increasing induration, especially the clay member 3.3. The salinity is remarkably low with regard to the calcium carbonate content (fig. 2.38—39.12) and the samples are distributed along the left guide line. One group of samples shows a deviating distribution, notably those from the clay member 3 (322—205 cm) and the adjoining stratum 205—195 cm which are considerably richer in sea salts than other samples of clay and clayey marl from core 39. This is possibly due to an increased content of silica gel from dissolved siliceous organisms in this bed. Thin sections of the deposit show typical dissolution traces in the radiolaria, but not in the foraminifera. These are generally not recrystallized. Crushing of the shells is frequent in the strata of clay and clayey marl, where also the traces of reworking are most frequent.

.13 Stratigraphy. The general features of the sequence coincide well with those from the East Eupelagic area both with regard to calcium carbonate distribution and location of *Coscinodiscus* maxima. The stratification is very marked and the correlation of the stages 1 to 6 is judged to be reasonably safe and the level C4 to be definite. There is evidence of changes in the rate of minerogenous sedimentation, which render it impossible to

recognize other details of the changes in the rate of biogenous sedimentation.

For the details of the suggested correlation, see abstract of this chapter and pl. 2.39.

Core 40

East Pacific Ridge

(Galapagos area)

Station no. 58.

Lat. 1° 04′ N, *Long.* 93° 20′ W.

Depth 2 820 m.

Length of core 1 017 cm.

Topography: Approaching the station from the SE, constant depth was recorded for appr. 13 km after which the bottom sloped gently downwards 200 m in 18 km. During the last 4 km before the station the bottom was at first constant, then rose slowly approx. 10 m. Another 20 m rise was recorded during work on the station. On the course again to the NE (fig. 2.40.0) constant or gently sloping bottom was first observed but later turned very irregular, short distances of even bottom being intercalated between mounts with an elevation up to 650 m. This type of topography prevailed during the 50 km of continued recording.

Abstract of interpretation. The stratification of core 40 appears to be strongly influenced by local disturbances of the deposition. As a result the normal eupelagic features of the East Equatorial Pacific stratigraphy are obscured and no possibility has been found

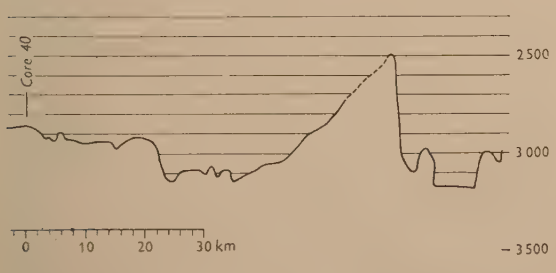

Fig. 2.40.0. Bottom topography in the vicinity of the station of core 40. Redrawn from Koczy (contribution to vol. IV).

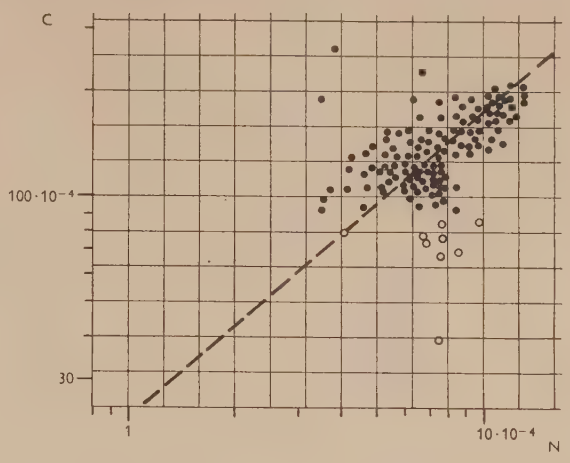

Fig. 2.40.4. Relation between carbon and nitrogen concentrations in core 40. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits. Open circles correspond to samples from core 40 A.

for correlating core 40. The spatial and statistical distributions of properties, however, yield valuable petrological information. The resemblance to the other cores from the Galapagos area is striking although a transition to the deposit type of the neighbouring parts of East Pacific Ridge is indicated.

.1 Calcium carbonate. Core 40 consists of 270 cm chalk ooze overlying marl ooze alternating with chalk ooze. As in the other cores from the Galapagos area a great proportion of the carbonate is present in the form of entire tests of foraminifera (fig. 2.40.7.1). The normal stratification with regard to calcium carbonate, found in undisturbed and normally deposited sequences in the East Equatorial Pacific, is absent in core 40.

.4 Organic matter. The carbon-nitrogen correlation of most samples is normal (fig. 2.40.4) with a tendency of the lower tail of the distribution to be displaced above the average equation line. The absolute concentrations of carbon and nitrogen are high as is the case with the other cores from this area. Core 40A shows abnormally low carbon values with regard to the nitrogen content, which probably

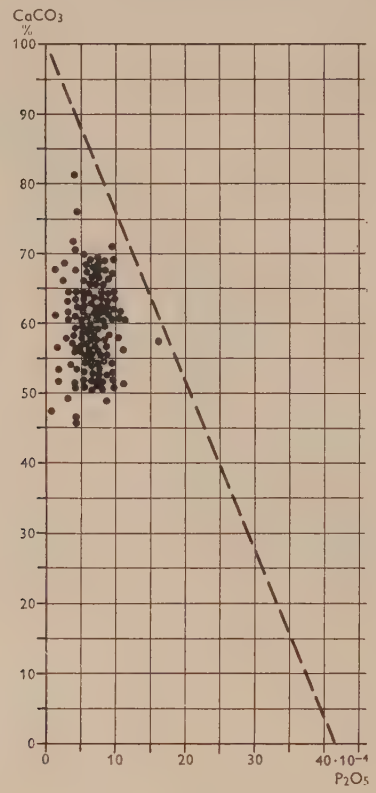

Fig. 2.40.5. Relation between concentration of phosphorus and concentration of calcium carbonate in core 40. The dashed line corresponds to the estimated eupelagic average.

depends upon the fact that this short core was stored in a plastic tube and had been in contact with the air for more than a year before it was sampled and analyzed. A similar case is core 41A.

A marked stratification exists with regard to the concentration of organic matter in core 40. There is a close general correlation between carbon and nitrogen but some interesting exceptions are found from the agreement of the trends of the two concentration curves. The most striking example is the disagreement between the nitrogen maximum at 542—460 cm and the carbon maximum at 590—520 cm. In order to prove whether this disagreement was caused by the decomposition of organic nitrogen compounds to soluble ammonium salts which had later migrated to a higher level, the amount of nitrogen present as ammonium salts was determined and plotted in the column N in pl 2.40. As is seen from the curve N_{NH_3} (scale at the bottom of the column) the ammonium nitrogen averages only appr. 10 % of the total amount of nitrogen and there is no marked increase of the concentration of ammonium salts in the nitrogen maximum stratum 542—460 cm. The reason for the mutual displacement of the carbon and nitrogen maxima at these levels is, therefore, not clear.

Recalculation of carbon on a carbonate free base [pl. 2.40, curve C: $(1-CaCO_3)$] reveals the fact that much of the regularity displayed by the curve C is due to the changing dilution with carbonates. From the bottom of the core up to appr. 850 cm and from appr. 600 cm to the top, the main features of the curves C and N are still clearly recognizable in the recalculated curves, but in the greenish layer 850—600 cm the regularity of the concentration changes of organic matter in the deposit appears to be a dilution effect. This is also generally the case in the laminated bed 984—948 cm.

.5 Phosphorus. As is seen from fig. 2.40.5 the concentration of phosphorus in core 40 is lower than is normal for eupelagic sediments but not as low as in cores 38 and 39. The richest samples of core 40 approach the eupelagic mean equation line. In this respect core 40 forms a transition from the Galapagos group, extraordinarily poor in phosphates to the abnormally rich group of the East Pacific Ridge, (cores 41—48). The main features of the stratigraphical distribution of phosphorus are not influenced by the calcium carbonate content as is seen from the curve P_2O_5: $(1-CaCO_3)$, pl. 1.40. It is obvious that the deposition of phosphorus has been subjected to considerable changes and it is probable that these are directly or indirectly due to changes in the composition of the minerogenous source material, but it is impossible to tell definitely what has caused these changes without further investigations. A fact which might be significant in this connection is that the

greenish coloured beds at 850—600 cm contain the strata richest in phosphate. As is indicated in § 2.40.6, the greenish colour is probably caused by ferrous iron compounds and possibly indicates the deposition of moderately weathered minerogenous material which has retained most of its original phosphate content. This assumption, however, must be confirmed by supplementary research.

.6 *Colour and pattern.* A remarkable feature is the greenish-yellowish grey bed at 850 — 600 cm between yellowish grey beds. The greenish colour is associated with the finest grades of the deposit and is probably caused by green organic matter or by ferrous compounds, the latter alternative being the more probable.

Only in one case does the colour shade deviate from c, viz. in the layer 30—8 cm which has the shade e (colour 2 lg). The blackness shows marked variations from the lowest value e, found in the greenish bed, up to the maximum value n in the sapropelic marl layer below this bed. All dark layers are rich in organic matter, but not all layers rich in organic matter are dark. This indicates that the black pigment is an organic compound or a group of compounds of varying concentration in the organic matter.

Worm holes, open or filled with loose sediment, have been found at several levels. The samples 40—17 x and 40—361 x are made up of the semiconsolidated fillings of two such holes. The composition of these samples does not differ markedly from the surrounding sediment.

Small dark brown lumps, approx. 1—0.1 mm in diameter, were frequently found, especially in the sapropelic bed 650—500 cm, but were not subjected to separate analysis.

Core 40 is exceptionally rich in the kind of structures which in this work are called type 40—873 x, after the prototype sample collected from 8 specimens in the layer 890—873 cm. Type 40—873 x consists of a prismatic body, approx. 0.5 cm thick, other dimensions unknown. The upper and lower surfaces show parallel striations and the cross section displays a parabolic pattern. A more detailed description is given in chapter 1.6. These structures are believed to be of organic origin although their exact process of formation is unknown. In this core their ground mass is yellowish — greenish white (1 ca) and the parabolic structures yellowish dark grey (2 nl). The surrounding material has also this colour (2 nl) and is rich in organic matter but comparatively poor in carbonate. 40—783 x is characterized by a normal or slightly increased amount of carbonate and a strongly decreased content of organic matter.

The bed 1 005—950 cm is distinctly laminated. The laminae usually have sharp boundaries and vary in thickness between a few centimeters and fractions of millimeters, the dark ones (2 ig) being the thickest and the whitish ones (2 ec) the thinnest. The dark laminae are relatively poor in foraminifera but do not otherwise differ markedly from the surrounding material with respect to the properties investigated. The samples 40—950, 966, 969 and 982 were extracted from dark laminae. Only one sample could be made of the whitish laminae (40—979), and this shows a decreased carbon content and a raised nitrogen content but is otherwise normal. The laminae of this bed do not give the impression of secondary precipitation but appear to be primary features. In pelagic deposits sharp boundaries of primary origin are scarce and in most cases where they appear they are related to slump structures, sand or silt layers, assorted shell fragments, etc., indicating a temporarily high rate of sedimentation. It is therefore believed that the bed 1 005—950 cm was deposited very rapidly, possibly representing distal facies of one or more graded beds. This belief is corroborated by the fact that the degree of fragmentation of foraminifera is abnormally low.

40—992 x, excavated from two dark rounded bodies, displays a normal carbon content but an increased nitrogen content.

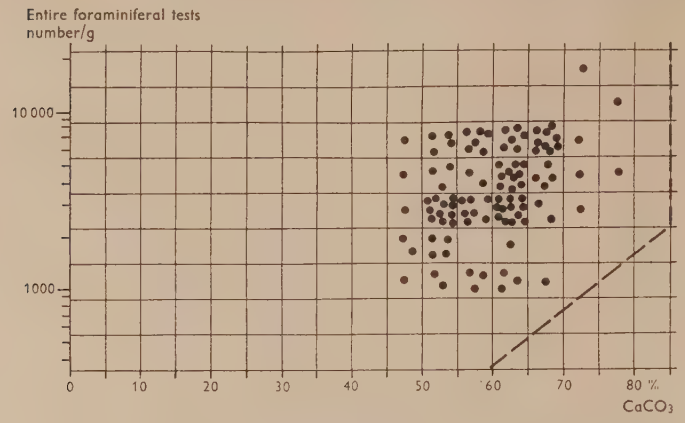

Fig. 2.40.7.1. Relation between concentration of entire foraminiferal tests and percentage of calcium carbonate. The dashed line illustrates the average eupelagic conditions.

The distribution is of the general Galapagos type, recorded by cores 38 and 39 (fig. 2.38.7.1. and 2.39.7.1).

.7 Foraminifera. With regard to faunal composition and concentration relationships (fig. 2.40.7.1—3), core 40 corresponds closely to the other cores of the Galapagos group (cf. § 2.38.7 and 2.39.7). The faunal changes recorded in pl. 2.40 are not regarded as a reliable basis for paleoecological interpretations, as there is evidence of mixing of faunas, redeposition and selective sedimentation.

.8 Radiolaria. The content of radiolaria is comparatively low and not subjected to strong variations. The radiolaria are in most cases strongly corroded, and therefore the present distribution can not be expected to reflect the original conditions at deposition.

.9 Diatoms. The frustules usually show signs of dissolution. Samples from the levels 190, 250 and 310 cm were subjected to analysis of the size distribution of *Coscinodiscus nodulifer*. No frequency maximum of big individuals was found.

.11 Mineral grains and rock fragments. Small numbers of microscopical grains of pumice and glass occur in many samples. A piece of pumice, weighing 0.6 g, was found embedded in the deposit at 106 cm.

.12 Diagenesis. There is a general diagenetical increase of strength from the top to the bottom with an average doubling of the strength each 425 cm. There are several significant deviations from this rule indicating

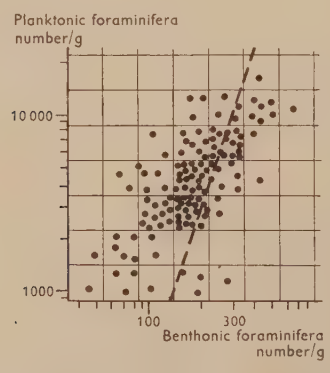

Fig. 2.40.7.2. Relation between concentration of entire tests of planktonic and benthonic foraminifera in core 40. The dashed line corresponds to the estimated eupelagic regression (§ 1.7.2).

The distribution is similar to that found in the other cores from the Galapagos area (fig. 2.38—39.7.2) and is believed to be influenced by the high rate of accumulation in this area. The group of high benthos concentrations connected to low plankton concentrations is derived from the stratum 740—700 cm in the greenish beds. It is not known whether these conditions are primary or secondary.

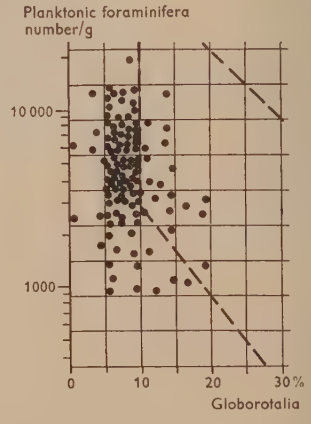

Fig. 2.40.7.3. Relation between concentration of entire tests of planktonic foraminifera and planktonic faunal percentage of *Globorotalia menardii* + *tumida*. The guide lines coincide roughly with the eupelagic equiprobability curve 0.05, i. e. the probability of occurrence of a eupelagic sample outside these boundaries is less than 10 percent.

The conditions are similar to those found in other cores of the Galapagos group (38 and 39), although the restriction to very low percentages of *Globorotalia* is not as marked as in 38 and 39.

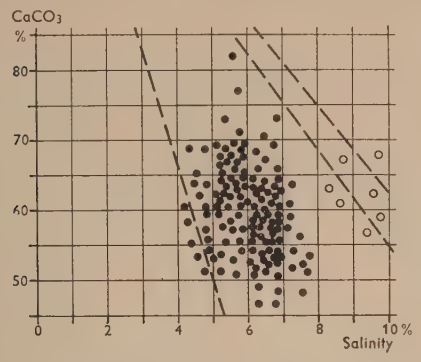

Fig. 2.40.12. Relation between calcium carbonate content and salinity in core 40. The dashed lines correspond to lines A, B and C in fig. 1.12.2.1. and 1.12.2.2. Open circles correspond to samples from core 40 A.

that also in this respect core 40 forms a transition to the East Pacific Ridge group, where solidification of single layers due to precipitation of silica occurs. The positive correlation between strength and calcium carbonate content, typical for deposits devoid of migrating silica, has disappeared in core 40. Abnormally high strength is found in the top layer 0—25 cm and in the bottom layer 1 003—1 018 cm. Both these pieces had been stored in cardboard tubes and some evaporation probably ocurred, and for this reason the measurements are not significant. Other abnormally high values which are most certainly original, appear in the beds poor in organic matter, 500—360 cm and 270—180 cm, as well as in the laminated marl ooze 984—948 cm and in the lowest part of the overlying chalk ooze layer.

The salinity ranges from normal to low with respect to the calcium carbonate content, with the exception of core 40 A (fig. 2.40.12). The skeletal remains of diatoms and radiolaria are as a rule strongly corroded. The foraminiferal tests are often recrystallized and partially dissolved.

.13 Stratigraphy. The abnormal calcium carbonate stratification and the frequency distribution of *Coscinodiscus nodulifer* indicate abnormal conditions, ecological or depositional. The statistical distributions of properties do not indicate ecological abnormalities but display a close resemblance to the other cores from the Galapagos area, including core 39, which could be correlated. On the other hand the topography of the surroundings, the strongly and irregularly varying (0.4—3.9) foraminiferal integrity index and the occurence of laminated beds, make it most probable that the lack of normal stratification is due to local depositional abnormalities. These abnormalities include varying rate of minerogenous sedimentation, varying sources of the minerogenous matter, and redeposition of sediment. Core 40 is therefore not regarded as a suitable object for comparative stratigrapical studies and it does not appear to be possible to correlate it with the cores from the Central Eupelagic Area.

Core 41

East Pacific Ridge

(North Equatorial carbonate facies)

Station no. 61.

Lat. 3° 20′ N, *Long.* 97° 53′ W.

Depth 3 400 m.

Length of core 560 cm.

Topography: Approaching the station from ESE the bottom profile was at first very irregular but during the last kilometers became level. Core 41 apparently was raised from the border of this level plain since, on the course to the ENE, irregular bottom was found within a distance of less than 1 km from the station (fig. 2.41.0).

Abstract of interpretation. Core 41 consists of chalk and marl ooze, deposited under abnormal conditions including redeposition and probably

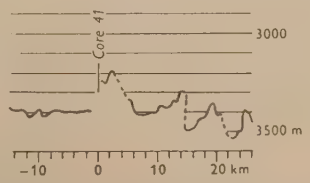

Fig. 2.41.0. Bottom topography in the vicinity of the station of core 41. Redrawn from Koczy (contribution to vol IV).

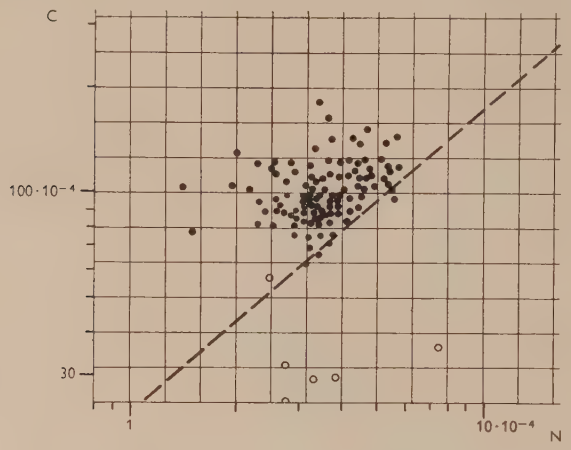

Fig. 2.41.4. Relation between carbon and nitrogen concentrations in core 41. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits. Open circles correspond to samples from core 41 A.

slumping. The sediment has been subjected to extensive post-depositional changes apparently brought about by rising solutions. No definite stratigraphical conclusions can be based on the sequence, which is however interesting from a diagenetical and metamorphical point of view.

.1 Calcium carbonate. As appears from pl. 2.41, the distribution of carbonate is very irregular in core 41, especially below the 2 m level. Down to this level the features of the distribution coincide roughly with the main features found in undisturbed eupelagic sequences. It is therefore possible that the marl ooze layer 202—182 cm corresponds to stage 3 or to the upper part of it and that the overlying chalk ooze comprises the stages 2 and 1. Below the supposed stage 3 the original distribution of carbonates appears to be extensively changed, partly through dissolution and reprecipitation, and partly through silicification. A rounded body, apparently a calcium carbonate nodule, was found at 211 cm and handed over to Professor C. Correns for a special investigation.

.3 Silica. Hard laminae of inorganically precipitated silica occur at several levels of core 41. For a closer description of these and related features, see the §§ 2.41 .6, .8, .9, and .12.

.4 Organic matter. In general the samples from core 41 are abnormally poor in nitrogen (fig. 2.41.4) which might depend on the advanced state of diagenesis. Like core 40 A, core 41 A was stored in a plastic tube and the peculiar C/N relationships are probably due to secondary changes occurring during storage.

.5 Phosphorus. The normal eupelagic correlation between carbonate and phosphate content does not exist in core 41 (fig. 2.41.5) which, like all cores from the East Pacific Ridge and in contrast to the cores from the Galapagos area, contains layers abnormally rich in phosphorus.

The vertical distribution of phosphorus in core 41 is of interest. The lower pale beds, poor in manganese and confined by the silica front at 329 cm, are very low in phosphorus

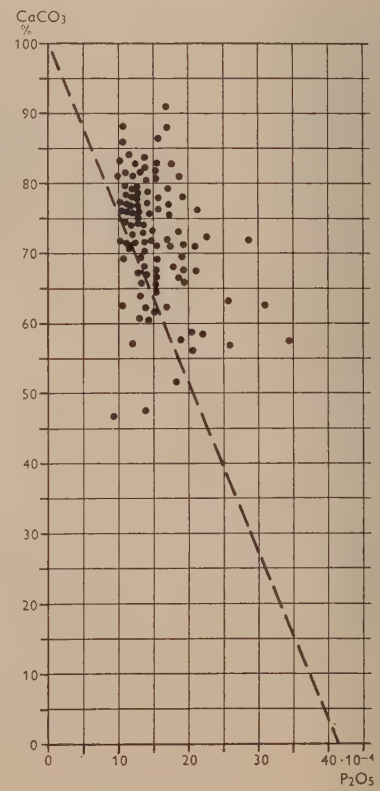

Fig. 2.41.5. Relation between concentration of phosphorus and concentration of calcium carbonate in core 41. The dashed line corresponds to the estimated eupelagic average.

(pl. 2.41). Immediately above the front there is a marked increase in phosphate content, which slowly decreases towards the top of the core. This distribution is believed to be caused by rising solutions which have dissolved and transported manganese, phosphates and silica from the lower beds to the upper.

.6 Colour and pattern. There is a very marked colour change at the silica front at 329 cm (pl. 2.6.1 and 2.6.7); the lower beds are pale greyish yellow and the overlying are dark brown becoming progressively lighter upwards. Chemical analysis shows that the dark colouration is due to the presence of manganese compounds.

Sharp colour boundaries occur frequently below the level 210 cm. In many cases the sharp colour changes are connected to diagenetical features such as silica fronts but in other cases it is possible that they are related to rapid changes in the rate of deposition. Diffuse irregular bodies, of a colour slightly deviating from that of the surrounding sediment, are frequent and are in some cases interpreted as slump structures and in others as secondary reaction bodies (including mud-eater traces.) One of these bodies was isolated from the level 158 cm, investigated separately and found to differ from the ground mass mainly by a high content of entire foraminifera with a higher percentage of *Globigerina* than the surrounding fauna. These facts appear to favour the slump structure interpretation in this case. Another similar body at 274 cm differed markedly from the surrounding deposit by having a higher content of carbon. The small size of the sample did not allow other analyses besides carbonate and carbon to be carried out. A light body at 316 cm, because of its location in a zone of secondary reaction, was believed to have its origin in secondary changes and did not reveal any considerable differences from the surrounding sediment with regard to the chemical properties investigated (spectrochemical results not taken into account). The silicified lamina at 329 cm differs in chemical composition from the surrounding sediment with respect to carbonate, carbon and salinity which are all lowered in the siliceous structure. Other structures of this type between 405 and 430 cm are also characterized by a lowered carbonate content.

The strongly silicified laminae, usually a few millimeters thick, are mostly characterized by a darker colour than the surrounding sediments (e. g. the series of silica laminae between 430 and 405 cm). The singular points in the blackness diagram (pl. 2.41) refer to these laminae in which a microstructure can in many cases be observed. The marl layer 536—520 cm (pl. 1.6.2) contains a series of thin dark laminae which appear to have been bent and dislocated, resting upon a 15 cm thick mottled layer. This layer is believed to contain redeposited clay balls rather than to be a normal sediment with secondary colour change due to post-depositional chemical reactions. This interpretation is supported also by the existence at a slightly lower level (551 cm) of an approx. 2 mm thick layer, abnormally rich in foraminifera (no count), and sharply confined downwards, which is believed to have been deposited from a turbidity current.

.7 Foraminifera. The concentration of foraminifera is subjected to extreme changes, from 400 to 27 000 per gram sediment. That these changes are due to depositional abnormities such as slumping and dissolution and not to variations of the production of foraminifera at the surface of the ocean, is demonstrated not only by structural observations but also by the lack of correlation between the concentration of foraminifera and of calcium carbonate (fig. 2.41.7.1). Mixing of faunas is indicated by the very irregular curves of genus percentage (e. g. *Globigerina* pl 2.41) and by the numerous strong deviations from the general correlation between concentrations

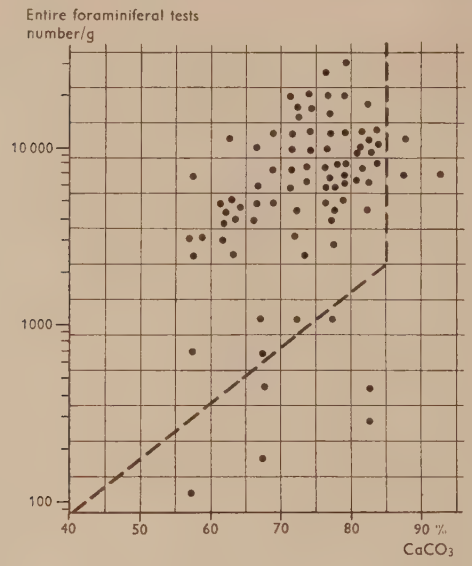

Fig. 2.41.7.1. Relation between concentration of entire foraminiferal tests and percentage of calcium carbonate. The dashed line illustrates the average eupelagic conditions.

The normal distribution, typical of an area with a high biogenous and minerogenous rate of accumulation, is extensively influenced by fragmentation which is in this case largely believed to be postdepositional.

of benthonic and planktonic foraminifera (fig. 2.41.7.2).

.8 Radiolaria. The distribution of radiolaria in core 41 does not reflect production as a function of time, partly because of abnormal deposition such as slumping, partly because of secondary dissolution. The corrosion of radiolaria is most marked in the lower beds but there is never a complete dissolution as found in the North Pacific clay area. The great amounts of inorganically precipitated silica at many levels is therefore believed to be derived mainly from lower levels than those sampled by core 41.

.9 Diatoms. The diatoms, which are more easily corroded than the radiolaria, appear to be entirely dissolved in the beds below 329 cm. Samples from the levels 184, 225, 247 and 302 cm were investigated with regard to the size distribution of *Coscinodiscus nodulifer*. No frequency maximum in big sizes was recorded.

.10 Other fossils. Single specimens of ostracodes were found in the upper chalk ooze at 112 and 118 cm.

.12 Diagenesis and metamorphosis. Most of the properties investigated in this core appear to be influenced by secondary changes and the diagenetical features have thus been referred to in the preceding paragraphs. As mentioned above the core can be divided into a lower and an upper bed from a diagenetical point of view, with the boundary being formed by the silica front at 329 cm. The lower bed is extensively indurated and laminae occur, so strongly cemented by silica that their strength can not be determined by means of the method used. Further, manganese and phosphorus appear to have been leached out of the lower bed and to have been reprecipitated in the lower part of the upper bed. The strength of the sediment indicates that extensive silicification is active also in the upper bed, at least below 180 cm.

The normal distribution of sea salts appears to have been extensively altered and several

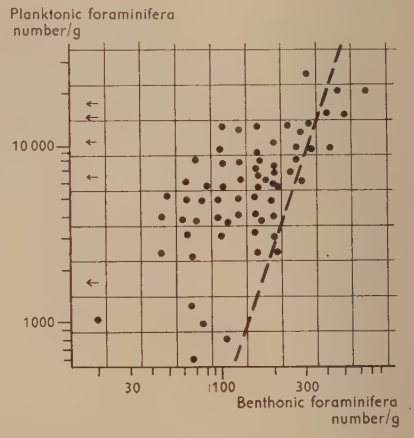

Fig. 2.41.7.2. Relation between concentration of entire tests of planktonic and benthonic foraminifera in core 41. The dashed line corresponds to the estimated eupelagic regression (§ 1.7.2).

Core 41 displays the highest concentrations of planktonic foraminifera found in the East Pacific. This feature may be primary and caused by a high rate of production combined with a moderate or low rate of minerogenous accumulation. The frequent occurrence of abnormally low benthos concentrations (including values indicated by arrows in the figure) and possibly also the extensive corrosion of tests, however, indicate that the deposition is abnormal and that the high concentrations of planktonic tests might at least be partly due to redeposition.

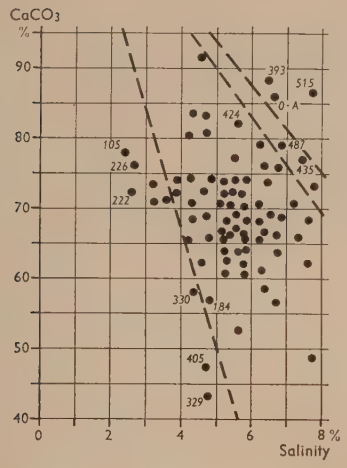

Fig. 2.41.12. Relation between calcium carbonate content and salinity in core 41. The dashed lines correspond to lines A, B and C in fig. 1.12.2.1 and 1.12.2.2.

abnormalities are displayed by the correlation Salinity/$CaCO_3$ (fig. 2.41.12). In most cases the silicified layers are deficient in salts, which can in some cases be traced to an excess in the adjacent layer. This phenomenon is further illustrated by core 42 (§ 2.42.12).

As mentioned in § 2.41.9 the diatom frustules are corroded and in the lower bed entirely dissolved. Both radiolaria and foraminifera display signs of corrosion but not as extensive as could be expected from the advanced state of diagenesis of the deposit. It therefore seems likely that the cementing matter is not or is only partly autochthonous.

.13 Stratigraphy. The original stratigraphical features of core 41 are very much obscured by metamorphic changes, and further, these original features are believed to have been to a great extent influenced by local abnormalities in the rate of deposition. It is therefore regarded impossible to recognize in this case those features of the normal eupelagic Equatorial sequences upon which a correlation can be based. From the carbonate distribution of the uppermost marl and chalk ooze bed (above 202 cm) it might be guessed that the marl ooze (202—182 cm) corresponds to stage 3 or to the upper parts of this stage and that the overlying chalk ooze comprises the stages 2 and 1. There is however no further evidence to prove this assumption.

Core 42

East Pacific Ridge

(North Equatorial carbonate facies)

Station no. 63.

Lat. 5° 42′ N, *Long.* 101° 41′ W.

Depth 3 200 m.

Length of core 778 cm.

Topography: Before and after the station, the recording was of a bad quality and did not permit the construction of a coherent bottom profile. Irregularities of more than 100 m were, however, indicated a few miles from the station. After stopping for station, variations in depth up to 40 m were recorded.

Abstract of interpretation. Core 42 displays the normal Equatorial eupelagic Pleistocene sequence of alternating chalk ooze and marl ooze. The core penetrates into stage 10 and the real top appears to be present. As in other stratigraphically checked cores from the Galapagos Area and the East Pacific Ridge the rate of minerogenous accumulation appears to be considerably higher (approx. average 30 % in core 42) than in the eupelagic environment of undisturbed lutite deposition. Changes in the deposition rate of non-calcareous matter, which generally prevent the recognition of substages in core 42, caused, during age 10, a considerable disturbance of the normal sequence.

Secondary silicification of the deposit is very pronounced and is accompanied by redistribution of phosphate, manganese and sea salts.

.1 Calcium carbonate. The carbonate content of core 42 is subjected to great and regular changes with depth. For reasons discussed in the following paragraphs and because of the general agreement in these changes between core 42 and the undisturbed eupelagic sequences of corresponding facies in the East Eupelagic area (e. g. cores 59 and 60), the varia-

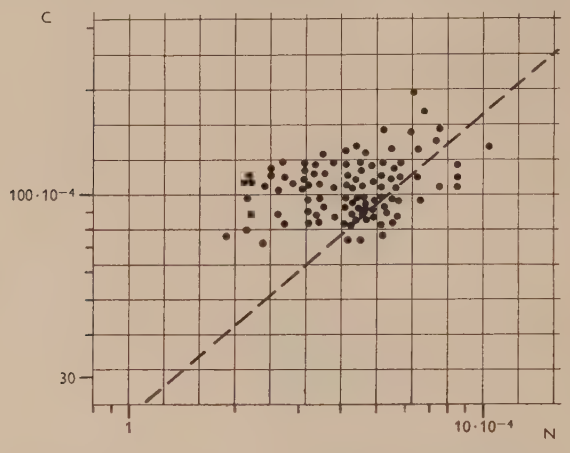

Fig. 2.42.4. Relation between carbon and nitrogen concentrations in core 42. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits.

tions are thought to be caused by the same agents in both cases. Most of the main features of the sequences are thus believed to be correlatable. Criteria of local depositional influences in core 42 are discussed in the following. Traces of secondary dissolution of calcium carbonate are abundant but do not appear to be followed by any considerable migration of the carbonates within the sequence (cf § 2.42.12).

.4 Organic matter. The correlation between carbon and nitrogen concentration is poor and, as in core 41, most samples are abnormally poor in nitrogen in view of the carbon content. This effect might be caused by the secondary mineralization of the deposit.

.5 Phosphorus. The slope of the correlation between carbonate and phosphorus (fig. 2.42.5) is in accordance with the conditions found in undisturbed eupelagic deposits. The average phosphorus concentration corresponding to any carbonate concentration is however approx. $4 \cdot 10^{-4}$ higher in core 42 than in the deposits from the East Eupelagic area. This is thought to be due to the higher concentration of manganese oxides in the minerogenous matter of the East Pacific Ridge deposits, which increases the ability of the sediment surface to precipitate phosphorus from the sea water. The higher concentration of manganese in its turn is believed to have its origin in the decaying volcanic matter in this area, whereas in the Central Eupelagic Area the minerogenous matter appears mainly to be derived from the lutite veil (*in sensu* KUENEN 1950).

Abnormally high values are separated by the arbitrarily drawn line A+, parallel to the eupelagic average equation in fig. 2.42.5. Values regarded as abnormally low are located to the left of line A—. The corresponding stratigraphical levels are indicated by A— or A+ in the column P_2O_5 in pl. 2.42. Both types of abnormalities are connected to colour structures (irregular lighter or darker bodies) believed to be due to secondary chemical reactions brought about by mud eating animals, bacteria

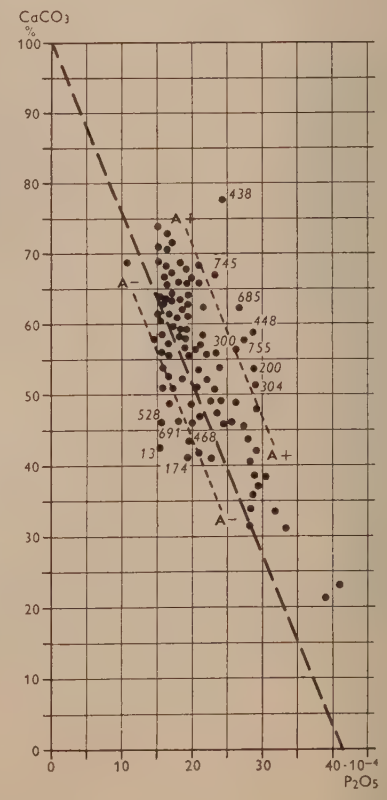

Fig. 2.42.5. Relation between concentration of phosphorus and concentration of calcium carbonate in core 42. The dashed line corresponds to the estimated eupelagic average.

or inorganic agents. Deficiencies in phosphate are in all cases connected to the light coloured structures (relatively poor in manganese), whereas the abnormally high values are found in the dark structures (comparatively rich in manganese). This is another observation indicating that under certain conditions manganese and phosphorus migrate together. The layer 468—438 cm appears to offer a good example of such migration. Both elements seem to have moved upwards from the upper part of the marl ooze bed and to have been reprecipitated in the lower part of the chalk ooze. The differing contents of finely dispersed manganese are roughly illustrated by the blackness of the deposit (pl. 2.42).

.6 Colour and pattern. The general colour of core 42 is a pale greyish yellow. The surface layer is characterized by a higher content of black (g) decreasing downwards and caused by the high amount of organic matter. The marl ooze member 3 (214—100 cm) is, unlike the older marl oozes, coloured blackish brown by manganese oxides. Another sharply limited zone of dark manganese coloration occurs in the chalk ooze member 2 at 195—192 cm between the zones of secondary precipitation of silica at 100 cm and 80—55 cm. These dark zones are regarded as parallels to the dark coloration of core 41 above the level 334 cm, and thus as results of secondary precipitation of manganese from rising solutions. The laminae of precipitated silica in the chalk ooze member 8 and the underlying marl ooze have an apparent blackness higher than the surrounding deposit. This increased blackness, however, does not appear to be caused by a pigment but to be an optical effect due to the translucency of the compact silica.

The chalk ooze member 8 is as a whole abnormally dark with regard to the high percentage of carbonates. The darkening appears to be caused by manganese which is supposed to have risen from the underlying marl ooze.

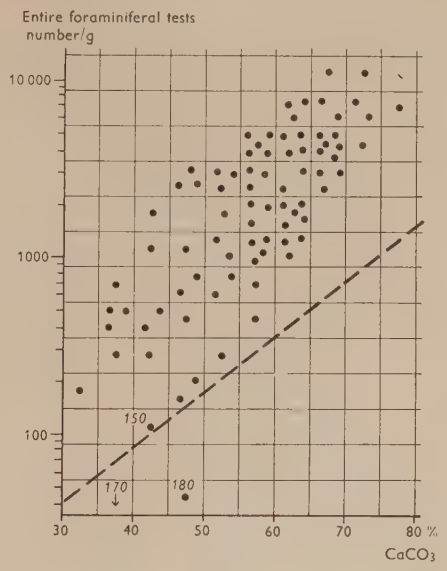

Fig. 2.42.7.1. Relation between concentration of entire foraminiferal tests and percentage of calcium carbonate. The dashed line illustrates the average eupelagic conditions.

The correlation is fairly good and of the type found in areas with a high rate of minerogenous and biogenous rac. The samples, which are abnormally low in entire tests, are derived from stage 3.

Striated layers of the type 40—873x occur at 209, 337, 348, and 545 cm.

Throughout the column the deposit is rich in irregular patches, diffuse or sharply delimited. Such features are especially abundant above the silicified layers.

Worm channels and digging holes, filled with loose material are found in the uppermost one meter layer. As the filling of such structures is usually dark it is difficult to recognize them by colour when, as in core 42, the surrounding deposit is also dark. The scarcity of observations of mud-eater traces at the lower levels of this core is thus probably not due to absence of these structures but to induration of the loose filling.

.7 Foraminifera. The proportionality between the log. number of foraminifera and concentration of carbonate is good, except in the samples from the layer 180—150 cm (fig. 2.42.7.1). In this stratum the number of foraminifera is abnormally low in view of the carbonate content. Thin sections of foraminifera

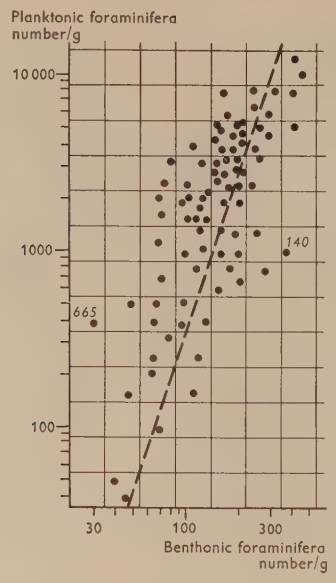

Fig. 2.42.7.2. Relation between concentration of entire tests of planktonic and benthonic foraminifera in core 42. The dashed line corresponds to the estimated eupelagic regression (§ 1.7.2).

The distribution is in good agreement with that found in the eupelagic area. The abnormal sample 140 is derived from a stratum, which other properties also indicate to have been subject to abnormal chemical redistribution. Sample 665 belongs to stage 9, and the abnormally low enrichment of resistant benthonic tests is believed to confirm the observation that the rate of minerogenous accumulation was abnormally high in the corresponding age.

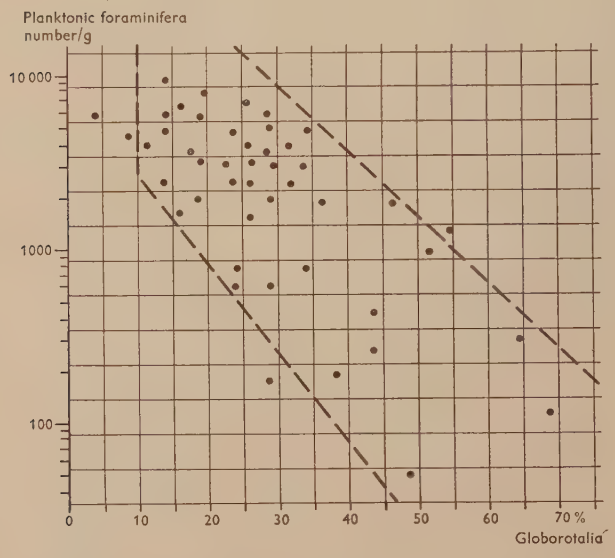

Fig. 2.42.7.3. Relation between concentration of entire tests of planktonic foraminifera and planktonic faunal percentage of *Globorotalia menardii* + *tumida*. The guide lines coincide roughly with the eupelagic equiprobability curve 0.05, i. e. the probability of occurrence of a eupelagic sample outside these boundaries is less than 10 percent.

from this layer indicate far-reaching recrystallization, and fragmentation by corrosion of the tests. Such very pronounced secondary changes are not found in other layers of core 42 with a markedly decreased rate of biogenous accumulation (stages 1, 5, 7, and 9). The secondary changes of structure of the fossils in the marl ooze member 3 are probably influenced by rising solutions which have manifested themselves also in abnormal manganese content, colour and silicification (cf § 2.42.6 and 2.42.12).

The slope of the correlation log. planktonic foraminifera-$CaCO_3$ in core 42 (fig. 2.42.7.1) is steeper than the average for the East Eupelagic area, due probably to the higher rate of accumulation of non-calcareous matter in core 42 (approx. 30 % higher than in core 60, average calculated down to stage 9).

The distribution of benthonic foraminifera (fig. 2.42.7.2) is in agreement with the East Eupelagic conditions.

The composition of the planktonic foraminiferal fauna is as a rule subjected to fairly small changes in core 42. These are believed to be ecologically significant as they are in conformity with the changes in calcium carbonate accumulation. The distribution of *Globigerina* and *Globorotalia* (fig. 2.42.7.3) is normal considering the concentration of planktonic foraminifera.

The zone of secondary mineralization in the marl ooze member 3 is abnormal also with regard to the composition of the foraminiferal fauna. The tendencies to a raised percentage of *Globorotalia* and a decreased percentage of *Globigerina* in connection with a lowered calcium carbonate content is quite normal. The changes recorded in the member 3 are, however, so much greater than the corresponding changes at lower levels that selective destruction might be suspected. Thus *Pulleniatina obliquiloculata* and the *Globigerina* species should in a higher degree than *Globoratalia menardii* and *tumida* be liable to frag-

mentation by corrosion and recrystallization beyond recognition.[1]) It appears, therefore, impossible to say to what extent ecological conditions at the surface of the ocean on the one hand and secondary changes of the deposit on the other, are responsible for the faunal composition found in the marl ooze member 3.

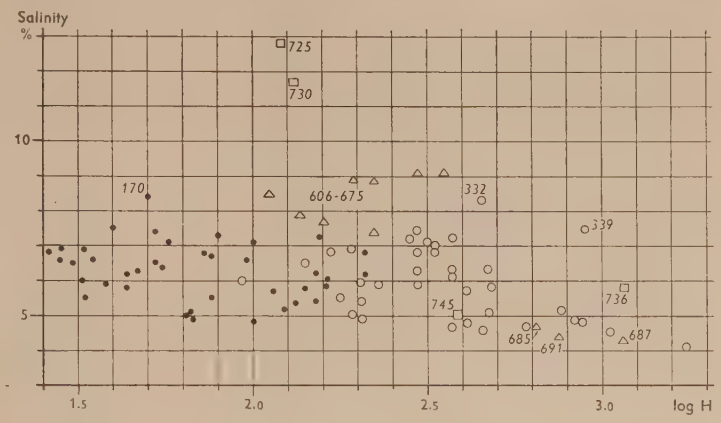

Fig. 2.42.12.1. Relation between salinity and shearing strength in core 42. Filled circles correspond to samples above the 300-cm level. Samples belonging to strata that are believed to have lost interstitial sea water because of extensive induration are indicated with the same signs as samples from such neighbouring strata that are believed to have received the excess salt solution.

.8 Radiolaria. The content of radiolaria in core 42 as a whole is low. Abundant traces of corrosion and dissolution of the siliceous fossils demonstrate that the low concentration of radiolaria is at least to some extent a secondary feature of the deposit. Extremely far-reaching dissolution is found at 554 and 180 cm. Studies of the size distribution of *Cyrtoidea* show that in samples where the corrosion is great, bigger forms prevail due to their higher grade of resistance.

.9 Diatoms. Diatom frustules are too scarce and corroded to allow a reliable size distribution analysis of *Coscinodiscus nodulifer.*

.10 Other fossils. Single shells of ostracodes were found at 0 and 214 cm.

.12 Diagenesis. Colorations and visible structures caused by secondary changes of the deposit have been referred to in § 2.42.6. Well developed silica laminae are found in the layers 694—687 cm and 560—538 cm. The shearing strength (pl. 2.42) indicates extensive silicification at several levels below approx. 240 cm. The strength maximum between 100 and 56 cm is believed mainly to be primary and due to the increased calcium carbonate content of this layer. The possibility of a beginning induration cannot, however, be excluded.

Silicification appears to be going on at the present surface of the sediment, which is characterized by abnormally increased strength. In this respect core 42 resembles core 88 from the West Pacific, where the surface layer is extensively cemented by silica. At least to some extent the secondarily deposited silica appears to be autochthonous or only slightly transported and to be derived from radiolaria and diatoms. The relationships between strength and salinity in core 42 are shown in fig. 2.42.12.1. As is seen from this figure there is no correlation between the two properties in the upper, only slightly indurated beds. When the silicification has gone so far that the shearing strength exceeds approx. 400 (log H = 2.6) the dissolved salts are partly displaced from the indurated layers. The salts driven off from the layer 745—736 cm, appear to have risen to the overlying layer 725—730 cm and the salts risen from the layer 691—685 cm are believed to constitute a part of the excess found in the layer 675—606 cm. These cases are indicated in fig. 2.42.12.1.

The water content of the sediment was determined directly in 11 samples and the results are indicated with points in pl. 2.42, col. Salinity. The scale for the water content is found at the lower end of the column.

[1]) In most other cases of selective destruction observed, the *Globorotalia* species are more extensively corroded than other foraminifera.

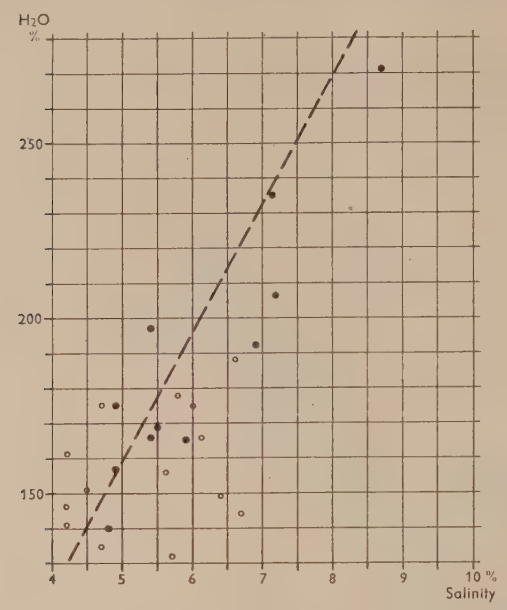

Fig. 2.42.12.2. Relation between water content and salinity of the sediment in extensively indurated cores. Open circles correspond to samples from core 42, filled circles to samples from core 43. The dashed line corresponds to the Atlantic average obtained from Gripenberg's and Hadding's analysis values (§ 1.12.1).

The water contents are correlated with the corresponding salinities in fig. 2.42.12.2. It is interesting to note that there is no very marked general decrease of water content with increasing induration. Expulsion of water thus appears to play a subordinate part in the induration process in this case. Further, it is evident from fig. 2.42.12.2 that where the salt has migrated it has largely been accompanied by the water so that no very marked deviations are found in the normal relationship salt/water.

The reason for the high strength of sample 339, rich in salt and water, is not understood.

.13 Stratigraphy. The general features of the stratification (pl. 2.42) agree well with the corresponding features in the undisturbed eupelagic and equifacial sequences from the East Eupelagic area and all stages down to 10 are recognizable. The rate of accumulation of non-calcareous matter appears to have been as an average approx. 30 % higher in core 42 than in the East Eupelagic area (cf 2.42.7) and has been subjected to changes strong enough to obscure the subordinate details of the production changes at the surface of the ocean. Substages are thus generally not recognizable in this core. In one case, recorded in the bed 744—710 cm, the change in the rate of minerogenous accumulation (possibly aided by secondary changes of the deposit) appears to have been big enough to influence the stratigraphical main features and to cause the intercalation of marl and clay in the chalk ooze member 10.

Due to the unusually high strength of the surface deposit, the top of the core appears to have remained undamaged by the coring device. This is indicated by the increased carbonate content of the top layer which is believed to correspond to Recent and Subrecent.

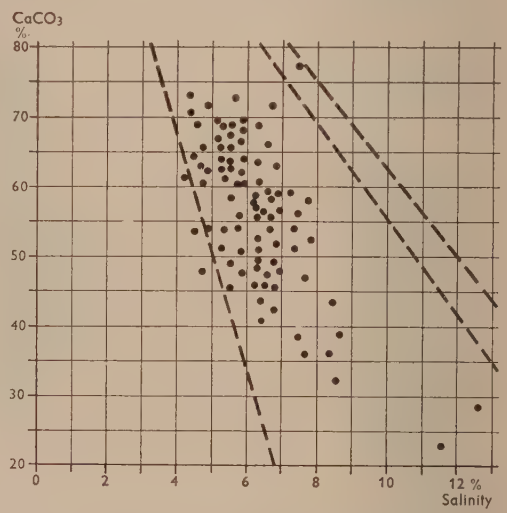

Fig. 2.42.12.3. Relation between calcium carbonate content and salinity in core 42. The dashed lines correspond to lines A, B and C in fig. 1.12.2.1 and 1.12.2.2.

Core 43

East Pacific Ridge

(North Equatorial carbonate facies)

Station no. 65.

Lat. 6° 21′ N, *Long.* 103° 42′ W.

Depth 3 465 m.

Length of core 930 cm.

Topography; irregular.

Abstract of interpretation. Core 43 consists of globigerina and globorotalia chalk oozes

with a few relatively thin layers of globorotalia marl and one layer of globigerina marl intercalated. The lithology of the sediment indicates that the lower and upper beds have been deposited under different environmental conditions, the older beds being richer in phosphate and foraminiferal fragments than the younger ones. The structure of one stratum near the bottom of the core indicates slumping. Both biogenous and minerogenous matter appear to some extent to be of detrital origin. Silica dissolved from radiolaria and diatoms does not seem to have migrated considerably but to cement the deposit in situ. The induration is not connected to expulsion of water.

Redeposition is believed to have obscured the normal eupelagic Equatorial sequence to such an extent that the core cannot be correlated.

.1 Calcium carbonate. Core 43 consists of chalk ooze with a few minor marl layers intercalated (pl. 2.43). The normal carbonate stratification of the East Eupelagic area is not repeated in this core. As will be demonstrated below there is reason to believe that considerable amounts of the fine grained carbonate is derived from older abraded deposits.

.4 Organic matter. The correlation between carbon and nitrogen is comparatively poor (fig. 2.43.4) and the samples are generally low in nitrogen when the nitrogen content of the neighbouring cores is taken into consideration. As a result the ratio C/N is generally high and strongly varying (15—93). The high value of C at 279 cm might originate in a contamination. The probability of this is increased by the fact that the sample 43—279 consists of the very end of a core section (43/05, lower end).

The inverse proportionality between calcium carbonate and nitrogen (pl. 2.43) possibly indicates that the decreased content of carbonates in the marl layers was caused by a reduced rate of calcium carbonate accumulation and not by an increased rate of accumulation of minerogenous matter. This statement is not valid for the marl layer 710—695 cm, where the nitrogen content does not noticeably differ from the over- and underlying chalk ooze.

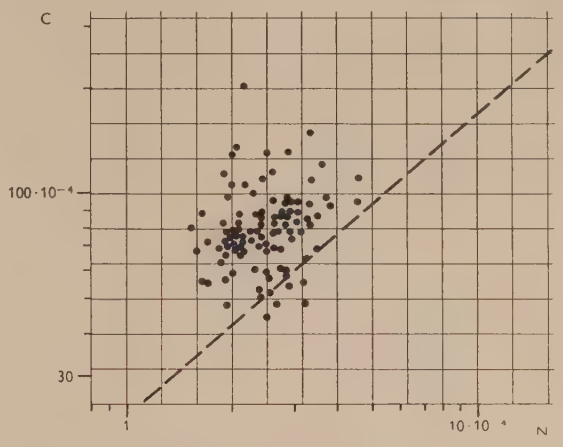

Fig. 2.43.4. Relation between carbon and nitrogen concentrations in core 43. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits.

.5 Phosphorus. As in other cores from the East Pacific Ridge, the slope of the correlation, between phosphorus and calcium carbonate is approx. the same as in the East Eupelagic area but the phosphorus concentration in relation to the carbonate content is abnormally high (fig. 2.43.5). The inferred reasons for this have been indicated in chapter 1.5.

As is seen from fig. 2.43.5, the dispersion is great in core 43. Abnormally high values are found to the right of line A+, drawn parallel to the guide line for the East Eupelagic samples and at an arbitrarily chosen distance from this line. These values are indicated with A+ in column P_2O_5 of pl. 2.43. Abnormally low values have been arbitrarily separated by line A— and indicated A— in the plate. From this is seen that the bed below approx. 430 cm, which is on the whole very rich in phosphorus, with one exception contains all the abnormally high values, whereas all values very low with regard to the carbonate content, are found above 430 cm. The exception to the

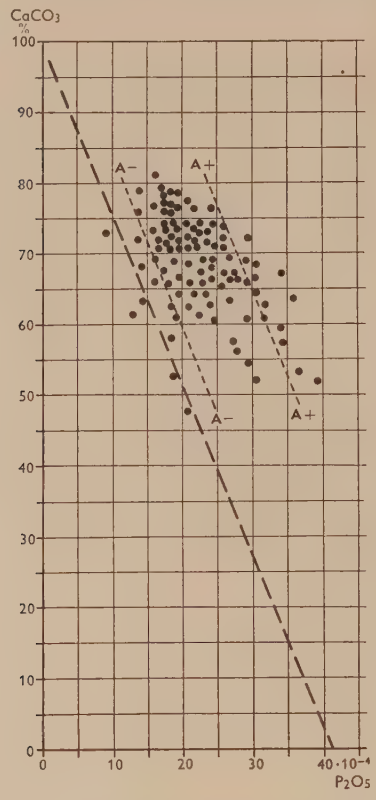

Fig. 2.43.5. Relation between concentration of phosphorus and concentration of calcium carbonate in core 43. The dashed line corresponds to the estimated eupelagic average.

rule of the high values is the sample 43—38 x, a light (3 ec) irregular body, which appears to have obtained phosphorus from the surrounding sediment which is abnormally low in this element. Both in the upper bed, which is poor in phosphate and in the lower, which is rich, the most marked anomalies are found in strata relatively poor in carbonates.

As there is no reason to ascribe the peculiarities of the vertical phosphate distribution in this core to secondary changes of the deposit it is assumed that the upper bed was deposited under other conditions than the lower one. This assumption is corroborated by the marked differences in the state of fragmentation of foraminifera in the upper and lower parts of the core (§ 2.43.7). It should be pointed out, however, that the boundary between high and low fragmentation is found at a higher level (232 cm) than the transition from abnormally high to abnormally low phosphate values (430 cm).

.6 Colour and pattern. The colour of the ground mass (pl. 2.43) varies between greyish yellow and dark brown, the latter colour generally being caused by an increased content of finely dispersed manganese and ferric compounds (cf § 2.43.11). In most cases the dark colour appears in layers of a decreased carbonate content, and the colouring oxide minerals might be primarily deposited. The surface layer and the likewise dark brown stratum 193—176 cm, are however located in chalk ooze and the coloration might be of secondary origin. The last mentioned stratum is characterized also by an increased content of carbon. The manganese content is higher than in the surrounding sediment and the dark colour disappears on reduction (boiling with sodium sulphite and hydroquinone in acid solution) but not on oxidation (boiling with ammonium peroxydisulphate or hydrogen peroxide). Further, comparable carbon contents at lower levels do not give rise to a corresponding darkening of the deposit. On account of these facts it is concluded that the dark colour of the stratum 193—176 cm is mainly due to the presence of authigenic manganese and iron oxidates.

The core is rich in structures of a very light colour (range a — 3 ec — 3 ea — 3 ca). These are irregular or tubular bodies, often with a core of the colour of the surrounding darker sediment. In cross section they are ring- or horse-shoe shaped or appear as irregular spots. The rings are frequently pointed on one side giving them a shape resembling the human eye. Eye, spot, and horseshoe structures are believed to be caused by secondary reduction or by prevented oxidation of manganese around embedded bodies of animals. These reduction structures are further described in chapter 1.6. An especially big reduction body was found at 797—794 cm.

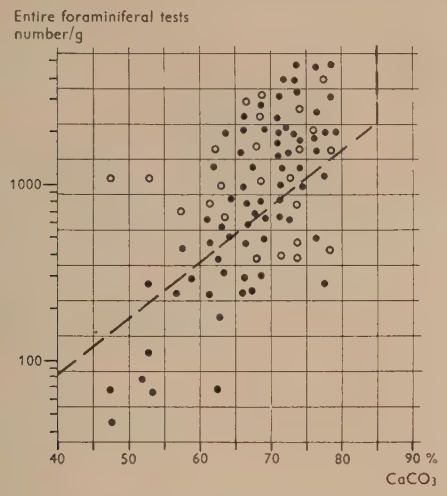

Fig. 2.43.7.1. Relation between concentration of entire foraminiferal tests and percentage of calcium carbonate. The dashed line illustrates the average eupelagic conditions. Open circles correspond to samples above and filled circles to samples below 232 cm.

The layer approx. 900—873 cm is rich in rounded and randomly oriented lumps of sediment of another colour (4 ie—ng) than the ground mass (5 ni — 6 pl) and comparatively rich in foraminifera. Enrichment of manganese has in some cases taken place at the border of the lumps. These are believed to be allochthonous and were possibly transported by slumping.

.7 *Foraminifera.* The concentration of planktonic foraminifera is strongly varying (between 50 and 5 000 per gram sediment). The variations are usually regular but do not always show the same trend as the variations in carbonate content. The slope of the correlation [entire foraminifera]—[calcium carbonate] is steeper than normal (fig. 2.43.7.1). With regard to this correlation, there appears to be no significant difference between the samples above and below 232 cm. The steep slope demonstrates that samples poor in foraminifera are abnormally rich in calcium carbonate in spite of the abnormally low degree of fragmentation (fig. 2.43.7.4). Thus the deposit contains an excess of fine grained carbonate presumably in the form of fragments of foraminifera or of coccoliths. Both these constituents are present, but the latter group appears to be of subordinate importance in this case. No quantitative measurements of the distribution of carbonate between coccoliths and foraminiferal fragments have been carried out in core 43.

The correlation entire foraminifera—percentage of *Globorotalia* (fig. 2.43.7.3) is normal. The sample to the left of the left guide line in the figure is 82. The samples to the right of the right guide line are 356, 365, and 377, 434, 485, 495, and 505. *Globorotalia* rises to faunal dominance in several zones and great parts of the chalk ooze and all marl ooze strata except the uppermost one have to be classified as globorotalia chalk ooze resp. globorotalia marl ooze (pl. 2.43).

The percentage of benthonic foraminifera is likewise subjected to considerable variations (2—112 %) and the correlation between planktonic foraminifera and benthonic foraminifera is good with the exception of the sample

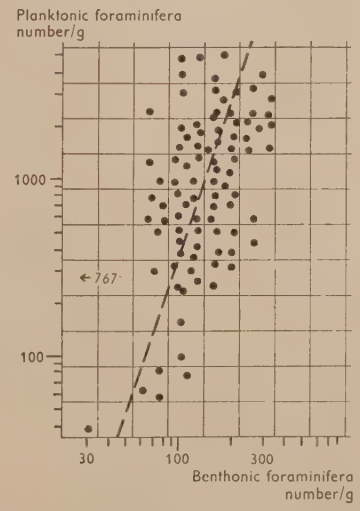

Fig. 2.43.7.2. Relation between concentration of entire tests of planktonic and benthonic foraminifera in core 43. The dashed line corresponds to the estimated eupelagic regression (§ 1.7.2).

The regression tends to be steeper than the eupelagic average, which is believed to indicate that the changes in foraminiferal concentration are, to a greater extent than is normal, due to postdepositional changes. The sample 767 is believed to be affected by extensive dilution with redeposited fine grained matter.

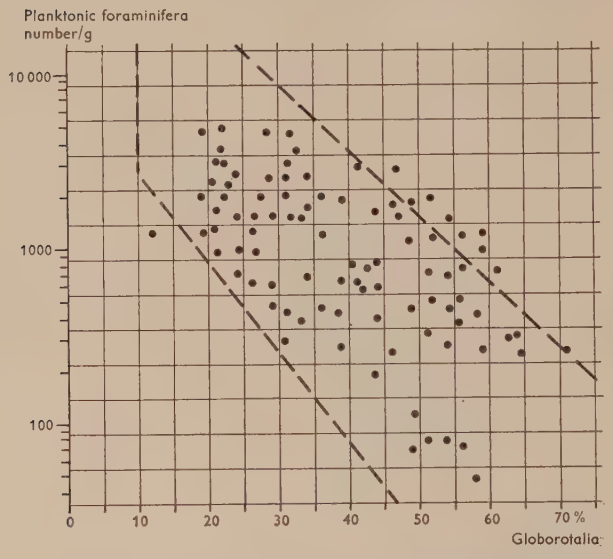

Fig. 2.43.7.3. Relation between concentration of entire tests of planktonic foraminifera and planktonic faunal percentage of *Globorotalia menardii + tumida*. The guide lines coincide roughly with the eupelagic equiprobability curve 0.05, i. e. the probability of occurrence of a eupelagic sample outside these boundaries is less than 10 percent.

767 cm (fig. 2.43.7.2). With regard to the fragmentation of foraminifera there is a marked difference between the beds above and below 232 cm, the upper bed being poorer (approx. average 2 500/g sediment) and the lower one richer (approx. average 7 000/g sediment) in fragments. The normal conditions of fragmentation are approached closer in the lower bed than in the upper one. If the differences found between the two beds were due to a change in the average rate of deposition from lower in the lower bed to higher in the upper bed, one would expect the average concentration of entire tests to be lowered and traces of mud-eaters to be more frequent in the lower bed. This is however not the case. It is, therefore, difficult to judge the kind of depositional changes responsible for the lithological differences between the upper and lower beds of core 43.

.8 Radiolaria. The concentration of radiolaria decreases continuously downwards to appr. 800 cm. Below this level the distribution is irregular. In all samples investigated the radiolaria are corroded, in some cases extensively, and there is thus reason to doubt that the distribution is original.

.9 Diatoms. The samples 154, 197, 242, 298, and 356 were investigated with regard to diatoms. Only in 197 a few, strongly corroded specimens were found, the diatoms apparently being completely dissolved in the other samples.

.10 Other fossils. Ostracodes occur in almost all layers in concentrations up to 85/g sediment.

.11 Mineral grains and rock fragments. All samples contain glass and palagonite grains $> 150\,\mu$. The concentrations are judged not to exceed 100/g sediment. Small manganese nodules ($< 0{,}1$ cm) occur frequently. Especially the following layers and samples are rich in these micronodules; 0, 72—122, 197, 232—242, 279—288, 308—356 (especially rich), 407—417, 445, 566, 625, 702, and 832—886. The layers rich in nodules thus do not necessarily coincide with the layers coloured dark brown by finely dispersed manganese oxides.

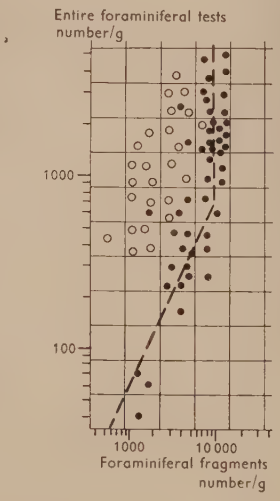

Fig. 2.43.7.4. Relation between concentration of entire foraminiferal tests and of foraminiferal fragments in core 43. Open circles correspond to samples above 232 cm and filled circles to samples below this level. The integrity index (quotient entire tests/fragments) is remarkably high in the upper beds, whereas the lower strata are normal with regard to fragmentation. These differences are believed to be due to a change in the depositional conditions. The nature of this change is not known.

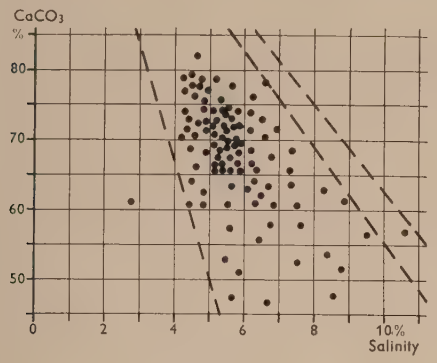

Fig. 2.43.12. Relation between calcium carbonate content and salinity in core 43. The dashed lines correspond to lines A, B and C in fig. 1.12.2.1 and 1.12.2.2.

.12 Diagenesis. The strength increases gradually downwards and the simultaneously decreasing concentration of radiolaria as well as the far-reaching corrosion of diatoms and radiolaria indicate that cementation with autochthonous silica is active. In the layers represented by the samples 566, 777, and 847, the normal relationship salt/water has been changed (fig. 2.42.12.2) to an abnormally high salinity of the interstitial water. As a general rule, however, there is no significant decrease of the water content with increasing depth, in spite of the increasing strength. Thus the induration in this case is not brought about by expulsion of water.

The samples 768 and 485 are both derived from the (lower) end of the core sections and the abnormally low strength of these samples might be caused by mechanical disturbance at coring or later.

.13 Stratigraphy. The lack of the normal eupelagic calcium carbonate stratification indicates that the deposits corresponding to core 43 are laid down under abnormal conditions. The correlation [entire foraminifera] [Ca CO_3] (fig. 2.43.7.1) and the appearance of thick beds of globorotalia chalk ooze (pl. 2.43, col. *Globorotalia*) reveal that there is an excess of fine grained carbonate present at least in some parts of the sequence. As has been mentioned above (§ 2.43.7) only subordinate amounts of coccoliths are found. The excess carbonate is believed to be detrital and derived from abrasion surfaces in the neighbourhood of station 65. Under the circumstances the faunal composition recorded cannot be relied upon as original. As both the paleontological and the petrological conditions thus indicate redeposition, core 43 cannot be correlated.

Core 44

East Pacific Ridge

(North Equatorial carbonate facies)

Station no. 66.

Lat. 6° 55′ N, *Long.* 104° 46′ W.

Depth 3 497 m.

Core length 967 cm.

Topography: Irregular (fig. 2.44.0).

Abstract of interpretation. Core 44 consists of 6 meters of alternating globigerina and globorotalia chalk ooze overlying 3½ meters of globigerina chalk ooze with a 10 cm stratum of globigerina marl ooze. The structures of the deposit and the relationships between properties investigated as well as the vertical distribution of these indicate that redeposition of locally abraded and of slumped sediments influence the stratigraphy. Due to these strong local disturbances, the normal eupelagic stratigraphical features are completely obscured and the core is regarded as not correlatable.

The strength of the sediment indicates induration of the intermediate beds.

.1 Calcium carbonate. The calcium carbonate content is high and irregular. The distribution of carbonate is believed to be influenced by

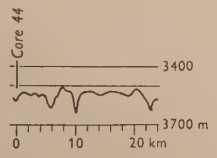

Fig. 2.44.0. Bottom topography in the vicinity of the station of core 44. Redrawn from Koczy (contribution to vol. IV).

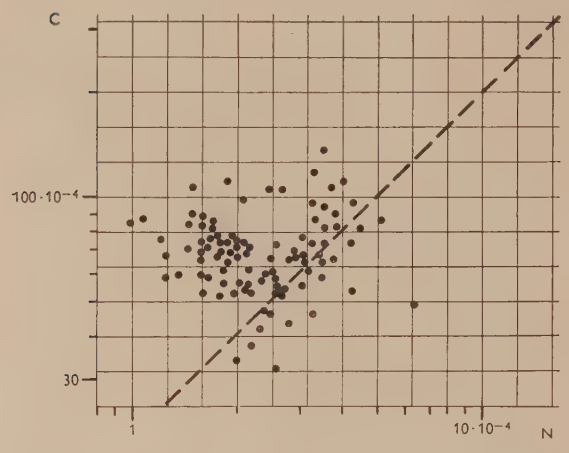

Fig. 2.44.4. Relation between carbon and nitrogen concentrations in core 44. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits.

redeposition in the same way as in core 43 which much resembles core 44.

.4 Organic matter. On the whole the core is intermediate in carbon and poor in nitrogen. The average ratio C/N is thus high but varies strongly as there is almost no correlation between these two components (fig. 2.44.4). The variance of the nitrogen content is considerably higher than that of the carbon content. There is a stratification with regard to nitrogen stratification, the beds 940—750 cm, 650—570 cm which is roughly parallel to the phosphorus and 410—300 cm being intermediate, 750—650 and 570—410 poor, and 410—0 rich in nitrogen. As reasons for these variations, changes in the source of detritus or changes in the rate of accumulation may be suggested. In the latter case the increased nitrogen and phosphorus contents would indicate a decreased rate of minerogenous accumulation.

.5 Phosphorus. The distribution of phosphorus with regard to the carbonate content (fig. 2.44.5) is of the general type of the East Pacific Ridge deposits; the increase of the phosphate content with decreasing carbonate content is greater than in the East Eupelagic deposits, which are used as a standard. The reasons for these conditions are treated in chapter 1.5.

The possible reasons for the stratification with regard to phosphate content (pl. 2.44) have been mentioned in the preceding paragraph (.4).

Sample 967 from the bottom of the core is abnormally rich in phosphorus with regard to the high content of carbonate.

.6 Colour and pattern. Structures believed to be of secondary origin (including mud-eater traces) of the types referred to in § 2.43.6 are frequent in core 44. Sharply limited round bodies with a diameter of approx. 1—3 cm are found between 654 and 641 cm, 621 and 609 cm, and between 252 and 220 cm. These structures might be allochthonous balls formed at slumping. A small ball, (0.5 cm diameter) abnormally rich in foraminifera was observed at 706 cm and is very probably of foreign origin.

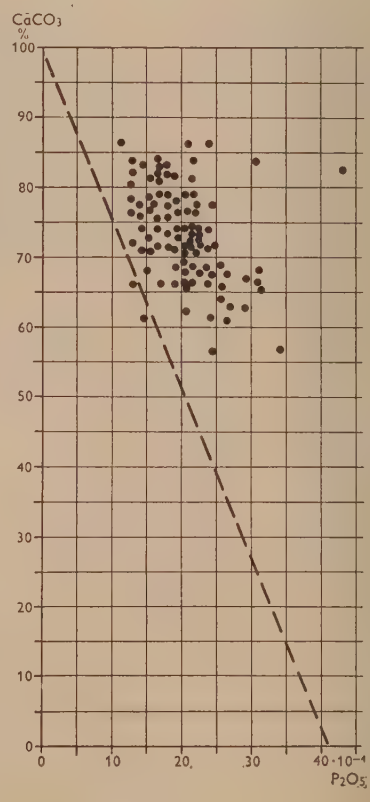

Fig. 2.44.5. Relation between concentration of phosphorus and concentration of calcium carbonate in core 44. The dashed line corresponds to the estimated eupelagic average.

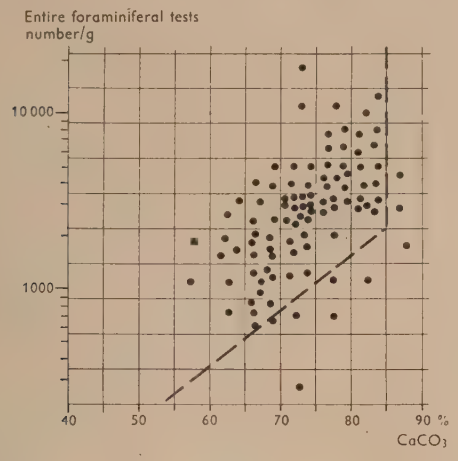

Fig. 2.44.7.1. Relation between concentration of entire foramineral tests and percentage of calcium carbonate. The dashed line illustrates the average eupelagic conditions.

The general colour is yellowish or brownish grey with the exception of the layer 60—30 cm which has the typical dark brown manganese-iron colour in spite of the high carbonate content.

.7 Foraminifera. The correlation between concentrations of foraminifera and of calcium carbonate is poor (fig. 2.44.7.1) and most samples are abnormally rich in foraminifera if compared with the East Eupelagic standard. The highest average content of foraminifera is found in the beds below 600 cm, where simultaneously the fragmentation index is low. These beds are also characterized by the lack of globorotalia chalk ooze which occurs intercalated in the globigerina chalk ooze of the upper beds. The correlation between concentration of foraminifera and percentage of *Globorotalia* (fig. 2.44.7.3) is fairly good, but single values are strongly deviating. The benthos values are not very well correlated to the foraminiferal concentration (fig. 2.44.7.2) and the slope of the average line is steeper than normal.

The distribution of foraminifera indicates that if core 44 has to some part been built up by redeposited sediments, the faunal constituents of these have not been extensively separated.

.8 Radiolaria. The concentration of radiolaria is low and their vertical distribution irregular. The highest average concentration is found in the uppermost bed, above 330 cm. It is possible that the lowering of the concentration downwards is a secondary feature and that silica, dissolved and reprecipitated in situ, causes the high strength of the intermediate and intermediate-lower beds. In these, however, no extremely far-reaching dissolution of radiolaria $> 150\ \mu$ was observed, although corrosion is common.

.9 Diatoms. The diatoms apparently are completely dissolved, as no single specimen was found in the samples investigated.

.10 Other fossils. Ostracodes occur in almost all samples in amounts of approx. 20/g sediment.

.11 Mineral grains and rock fragments. Volcanic glass, palagonite and manganese micronodules occur sporadically. Greater amounts of glass and palagonite (a few hundred grains/g) were observed at two levels only, viz. at the present surface and at 505 cm.

.12 Diagenesis. The good correlation between carbonate content and salinity (fig. 2.44.12) is

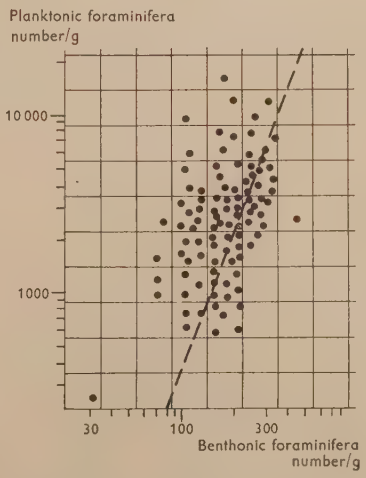

Fig. 2.44.7.2. Relation between concentration of entire tests of planktonic and benthonic foraminifera in core 44. The dashed line corresponds to the estimated eupelagic regression (§ 1.7.2).

The distribution is similar to that found in core 43 (fig. 2.43.7.2).

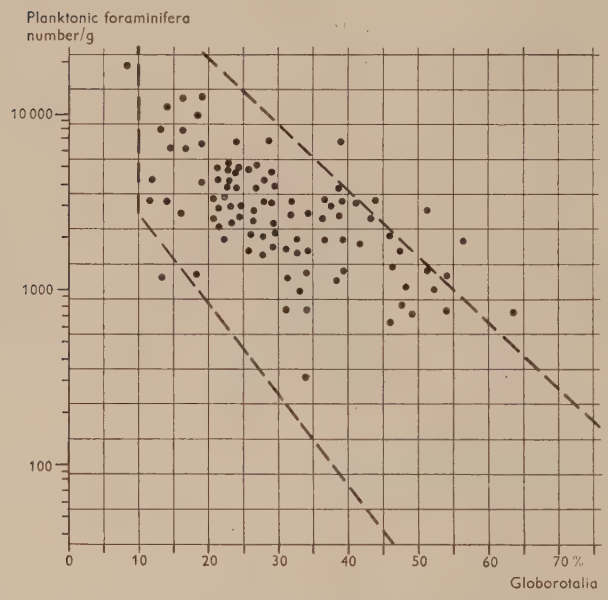

Fig. 2.44.7.3. Relation between concentration of entire tests of planktonic foraminifera and planktonic faunal percentage of *Globorotalia menardii* + *tumida*. The guide lines coincide roughly with the eupelagic equiprobability curve 0.05, i. e. the probability of occurrence of a eupelagic sample outside these boundaries is less than 10 percent.

well preserved, which indicates that the diagenesis has generally not gone far enough to start displacement of salts. Layers abnormally rich in salt, are indicated A+ in pl. 2.44 and are labelled in fig. 2. 44.12. Samples from the salinity minima surrounding the abnormal maxima are also indicated in the figure. With one single and not very pronounced exception (832)

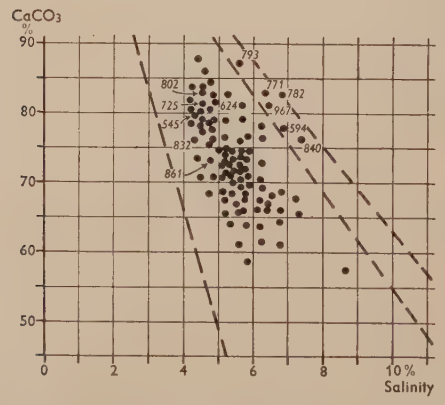

Fig. 2.44.12. Relation between calcium carbonate content and salinity in core 44. The dashed lines correspond to lines A, B and C in fig. 1.12.2.1 and 1.12.2.2.

these are quite normal. The excess of salt in the abnormal layers thus appears not to be derived from the adjoining deposit but might be original or due to lateral enrichment. It is interesting to note that all the abnormal layers are connected to strength minima.

The strength culminates at 710 cm (pl. 2.44) and thus decreases both upwards and downwards. This might be an effect of beginning silicification of the intermediate beds.

.13 Stratigraphy. The sequence appears to be strongly influenced by local redeposition of suspended detritus and of slumped material. The stratigraphy is thus believed to reflect local events only, which are not easily interpreted.

Core 45

East Pacific Ridge

(North Equatorial carbonate facies)

Station no. 68.

Lat. 7° 40′ N, *Long.* 106° 21′ W.

Depth 3 725 m.

Core length 975 cm.

Topography: Irregular, same type as at station 66 (core 44).

Abstract of interpretation. Core 45 consists of globigerina chalk ooze, and globigerina and globorotalia marl ooze alternating with clay. Although the rate of minerogenous accumulation is fairly high (appr. 120 % of the corresponding rate in core 60, calculated as average down to stage 11) the changes in this rate do not appear to have been big enough to obscure the main features or even the details of the normal eupelagic stratigraphy down to stage 13.

Reduction bodies and traces of bottom scavengers are frequent. Selective fragmentation and dissolution have influenced the composition of the foraminiferal faunas of the clay members. Secondary migration of manganese towards the sediment surface appears to be going on.

.1 Calcium carbonate. The calcium carbonate concentration is subject to strong and regular

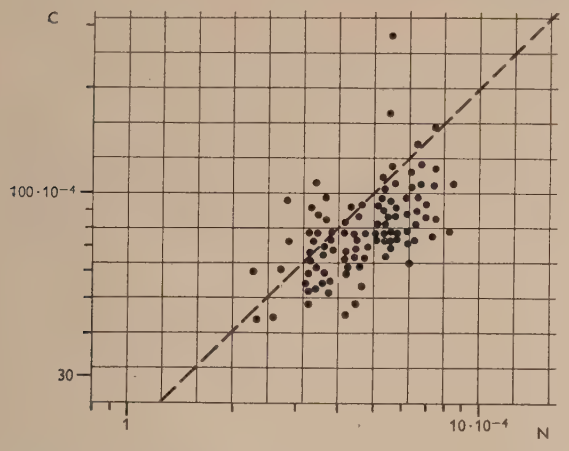

Fig. 2.45.4. Relation between carbon and nitrogen concentrations in core 45. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits.

variations (14—68 %) and the main features of the normal eupelagic carbonate stratification appear to be retained. Primarily deposited foraminifera, entire and secondarily fragmented, appear to form the main part of the calcium carbonate. The presence of some redeposited detrital calcium carbonate, presumably in the form of foraminiferal fragments, is indicated at a few levels. The clay member 7 is abnormally low, and the lowest half meter layer of the core too high in carbonate with regard to the corresponding concentration of planktonic foraminifera and faunal composition.

.4 Organic matter. Carbon and nitrogen are fairly well correlated (pl. 2.45 col. C and N, fig. 2.45.4) and both generally inversely proportional to the carbonate content. The greatest variations are found in the carbon concentration ($4—18 \cdot 10^{-3}$) but the changes in nitrogen with depth are more regular and more closely correlated with the carbonate content. The conspicuous nitrogen maximum at 66 cm is abnormal in so far as it neither corresponds to a significant increase in the carbon concentration nor to a considerable decrease in the percentage of carbonate. The significance of this nitrogen maximum is not understood.

Abnormal influx or preservation of organic matter is indicated at the levels 900—875 cm, 583—565 cm, and 509—498 cm by maxima in the carbon and nitrogen curves which are not accompanied by normally decreased carbonate concentrations. Although a minimum in the distribution of organic matter characterizes the globigerina chalk ooze layer 735—695 cm, this minimum is not as deep as one would expect from the high carbonate content. The reason for this is not seen.

As a general statement it might be said that the distribution of organic matter approaches normal eupelagic conditions, although at some levels local depositional influences are indicated.

.5 Phosphorus. The linear correlation between phosphate and carbonate is fairly good (fig. 2.45.5) and of the general East Pacific Ridge type, the average equation being displaced

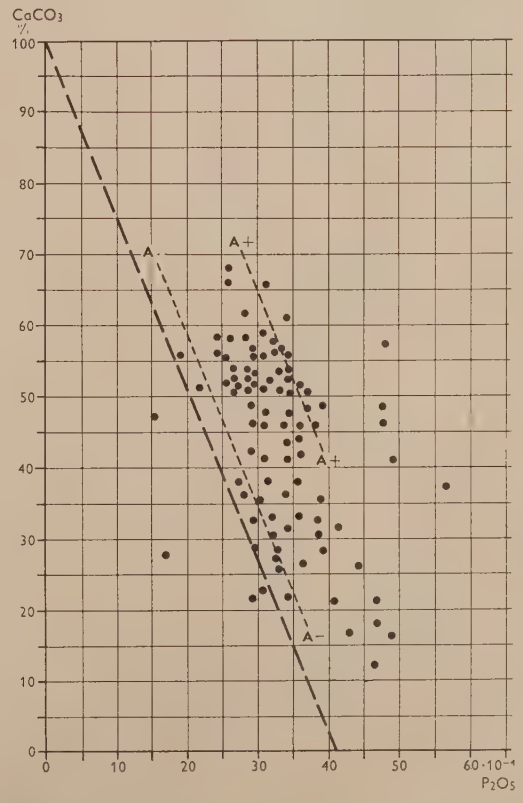

Fig. 2.45.5. Relation between concentration of phosphorus and concentration of calcium carbonate in core 45. The dashed line corresponds to the estimated eupelagic average.

TABLE 2.45.6.

Location	Sample nr	$CaCO_3 \cdot 10^3$	$C \cdot 10^4$	$N \cdot 10^5$	$P_2O_5 \cdot 10^4$	Mn
Surrounding dark sediment above roll	45—209 x	281	60	49	17	high
Whitish ground mass of the roll	—210 x	446	159	74	50	low
Yellowish red rim of the roll	—211 x	317	145	—	32	—
Dark core of the roll	—212 x	166	184	—	35	high

to the right of the East Eupelagic guide line to which it is approximately parallel.

Abnormally high and low values occur at several levels (fig. 2.45.5). The most pronounced positive anomalies are indicated A+ in pl. 2.45 col. P_2O_5 and the negative A—. In most cases these anomalies are probably caused by changes in the source of the local minerogenous matter or by changes in the supply of manganese and iron, which appear to affect the rate of precipitation of phosphorus. In the case of the samples 209 x and 210 x the abnormities are however certainly due to secondary redistribution in the corresponding reduction structure (cf § 2.45.6).

.6 Colour and pattern. There is a general tendency for the hue to turn from yellowish to reddish and for the blackness to increase upwards in core 45. As a result the colour shifts from greyish yellow in the lowest beds to blackish brown in the top bed. This change is probably due to an increased accumulation of manganese and iron in the upper part of the sequence. It is difficult to prove whether such an increase of the accumulation is due to primary deposition or to precipitation from rising solutions, which have leached the lower beds. The latter possibility appears to be the most probable one, the more so as at least small distance migration of manganese is frequent in the numerous reduction structures present in this core. One of these (213—209 cm) is the biggest reduction body encountered in the East Pacific material and has the form of an oval roll 3 × 1.5 cm in cross section, of unknown length, and containing a central core 0.5 × 1 cm in cross section with a colour identical with the blackish brown (5 ni-pn) of the surrounding deposit. The roll is yellowish white (3—2 ea) except for the core and an approx. 1 mm broad rim which is greyish-yellowish red (4—3 lc). Three small nodules were found close to the upper boundary of the roll. Special samples were extracted according to table 2.45.6.

In this case, too, the content of organic matter of the samples indicates that the reduction was caused by a decaying body or part of the body of an organism. The high carbonate content of the reduced deposit might partly be due to the removal of most of the iron and manganese and possibly also to conditions preserving the carbonate from dissolution. It is interesting to note that in this case the phosphorus has apparently not migrated together with the manganese. The manganese content was preliminarily estimated from the intensity of the spectral line Mn 2 801 Å.

Worm channels and other cavities, open or filled with loose or indurated sediment are frequent, especially in the beds approx. 740—509 cm. A round cavity at 509 cm contained a great number of oval faecal pellets, 1.5—2 mm long.

Rounded bodies with a maximum size of a few centimeters (fig. 1.6.0) are common especially in the clay strata. It is difficult to prove whether these bodies are allochthonous sediment balls or fillings of mud-eater cavities. Their association with typical worm channels however makes the latter alternative most probable.

.7 Foraminifera. The number of planktonic foraminifera per gram sediment varies strongly,

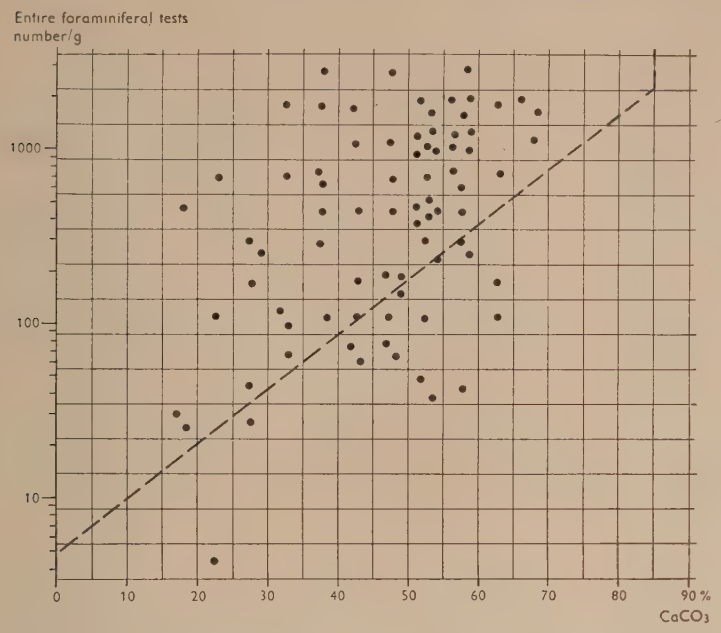

Fig. 2.45.7.1. Relation between concentration of entire foramineral tests and percentage of calcium carbonate. The dashed line illustrates the average eupelagic conditions.

viz. from 4 to more than 2 000 (pl. 2.45), the changes being due to a varying rate of accumulation of foraminifera and to a varying intensity of fragmentation. In most cases the trends of the curves of concentration of foraminifera and of calcium carbonate are in a good general agreement but the correlation between these two properties displays considerable scattering (fig. 2.45.7.1). The most pronounced abnormalities shown in this figure and characterized by a too high concentration of foraminifera with regard to the carbonate content are located in the clay members 7 and 9 and the intercalated marl ooze member 8. Too high carbonate contents compared to the concentrations of foraminifera are found especially in the lower part of the chalkmarl ooze member 12.

The distribution of *Globorotalia* in core 45 is of principal interest. Dominance of *Globorotalia* is mostly found in connection with a low rate of accumulation of foraminifera (low concentration of carbonate and foraminifera, high percentage of benthonic foraminifera). Significant irregularities are, however, frequent in this core. In some cases dominance of *Globorotalia* is found immediately below the accumulation minimum (698—676 cm and 368—358 cm) or bordering the minimum (840—826 cm, 796—774 cm). In the minima corrosion and fragmentation are extensive (the integrity index sometimes reaching values of 0.1 or lower). Inspection of the fragments as well as of thin sections of naturally and artificially corroded assemblages reveals that the *Globorotalia* species present are more easily corroded and crushed than the *Globigerina* species. These in their turn have suffered a more extensive destruction than most benthonic species, the tests of which are mostly small and apparently resistant to corrosion and mechanical disintegration. The percentage distribution of *Glo-*

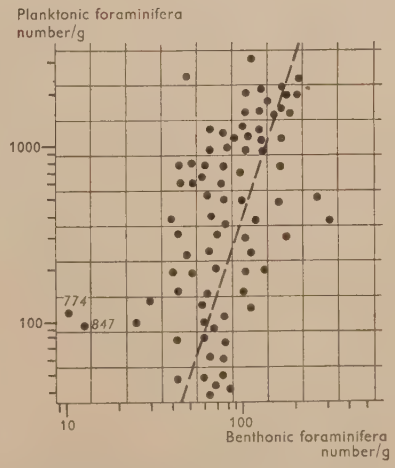

Fig. 2.45.7.2. Relation between concentration of entire tests of planktonic and benthonic foraminifera in core 45. The dashed line corresponds to the estimated eupelagic regression (§ 1.7.2).

The far-reaching dissolution and disintegration is reflected by the abnormally high enrichment of benthonic tests in strata poor in foraminifera. — The reason for the deviation of samples 137, 774 and 847 is not known, neither is that for the abundance in samples 6 and 16.

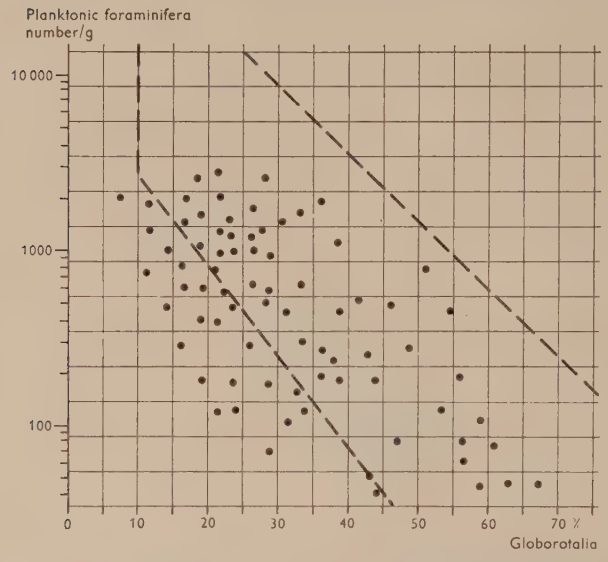

Fig. 2.45.7.3. Relation between concentration of entire tests of planktonic foraminifera and planktonic faunal percentage of *Globorotalia menardii + tumida*. The guide lines coincide roughly with the eupelagic equiprobability curve 0.05, i. e. the probability of occurrence of a eupelagic sample outside these boundaries is less than 10 percent.

The normal correlation between concentration of planktonic foraminifera and percentage of *Globorotalia menardii + tumida* is strongly counteracted by selective dissolution which tends to decrease the original percentage of *Globorotalia*.

borotalia as well as of benthonic foraminifera is thus influenced by two factors; the rate of production as compared with other groups and the selective destruction by corrosion and crushing. That the latter effect is of great relative importance in core 45 is seen also from the relationship conc. entire foraminifera: percentage of *Globorotalia* (fig. 2.45.7.3). A considerable number of the samples shown in this graph have an abnormally low percentage of *Globorotalia* with regard to the concentration of entire foraminifera.

The distribution of benthonic foraminifera (fig. 2.45.7.2) indicates that extensive secondary enrichment of benthos by selective dissolution has taken place in most strata with a low content of foraminifera.

.8 Radiolaria. The core is as a whole poor in radiolaria and those present are often extensively corroded. The distribution of concentration is irregular and appears to be strongly influenced by secondary dissolution. The most far-reaching corrosion and the lowest average concentration is found in the most strongly indurated bed comprising the bottom 220 cm of the core.

.9 Diatoms. The concentration of diatom frustules has apparently been lowered by dissolution, and most frustules found are corroded. Three samples extracted from the members 3—4 were found to contain enough identifiable individuals to permit analysis of the distribution of *Coscinodiscus nodulifer* (table 2.45.9).

From the table is seen that in spite of the disturbances brought about by secondary dissolution the typical increase of large sized specimens of *Coscinodiscus nodulifer* in stage 4 can still be traced in core 45.

.10 — .11 Other fossils, rock fragments and mineral grains. A few ostracodes are found in almost all samples. Fish teeth were observed in three cases. Glass and palagonite are scarce. Manganese micronodules are comparatively frequent (max. 42/g) in the top half meter bed.

.12 Diagenesis. The strength of the deposit increases downwards to approx. 3 m where it

TABLE 2.45.9.

Upper limit of size group, μ	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	Number counted
Percentage in size group. Sample 45—150	0	3	17	25	22	13	9	6	3	1	0	0	0	0	0	0	0	0	335
Percentage in size group. Sample 45—252	0	2	12	31	20	8	4	7	3	4	2	5	1	0	0	0	0	1	100
Percentage in size group. Sample 45—301	0	4	12	20	23	18	4	5	4	4	1	3	1	0	0	0	0	0	75

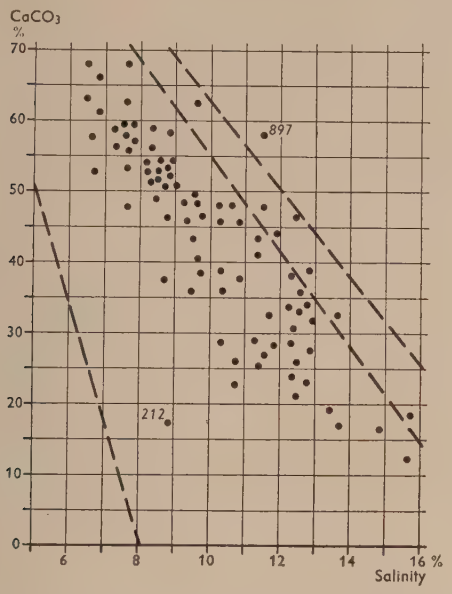

Fig. 2.45.12. Relation between calcium carbonate content and salinity in core 45. The dashed lines correspond to lines A, B and C in fig. 1.12.2.1 and 1.12.2.2.

keeps constant around 100 down to 7,5 m. The induration above this level can be regarded as normal, although the composition of the deposit has almost completely lost its influence on strength. Below 7,5 m the induration is abnormally high which might at least partly be due to dissolution of siliceous fossils and reprecipitation of the silica in situ. The strongest positive anomaly in salinity is also found in this bed (897 cm) (fig. 2.45.12). The most pronounced deficiency in salt with regard to the carbonate content is found in the sample 212 cm from the dark core of the reduction body.

Corrosion is not very marked and fragmentation is low in the layers rich in carbonate (integrity index above 1.5 in the members 2,4, and 6). In the clay strata, however, corrosion has been very active. Selective dissolution and fragmentation have extensively changed the original relative faunal composition, the absolute fossil concentrations, and apparently also the carbonate content of the deposit.

.13 Stratigraphy. The major and many of the minor features of the stratification of core 45 are believed to agree closely with the normal equifacial eupelagic sequence. It is difficult to judge exactly how much of the top of the core is missing. The distribution of foraminifera indicates the probability, however, that at least the substage 1.3 has been sampled. The subdivision of stage 3 is regarded as fairly safe, and stage 4 is confirmed by the size distribution of *Coscinodiscus nodulifer*. Stage 7 appears to be abnormal with regard to concentration of foraminifera (high) and percentage of benthos (low), which might, however, be due to the fact that only one sample from this stage was subjected to microscopical analysis. The subdivision of stage 8 and of stage 9 is regarded as fairly safe. The location of the lower boundary of stage 12 is uncertain but the distribution of foraminifera indicates that it is situated at approx. 935 cm. If this is true, the bottom layer of the core corresponds to stage 13 or parts of this stage.

Core 46

East Pacific Ridge

(North Equatorial carbonate facies)

Station no. 69.

Lat. 8° 22′ N, *Long.* 108° 0′ W.

Depth 3 775 m.

Core length 979 cm.

Topography: The core was raised from the slope of an approx. 100 m high shield formed elevation bordering a plain, approx. 12 km broad (fig. 2.46.0).

Abstract of interpretation. Stratigraphically and petrographically core 46 very closely resembles core 45. The average rate of accumulation of non-calcareous matter is slightly

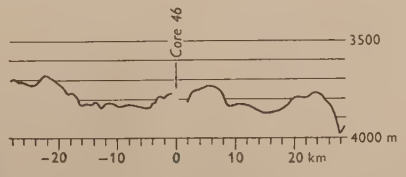

Fig. 2.46.0. Bottom topography in the vicinity of the station of core 46. Redrawn from Koczy (contribution to vol IV).

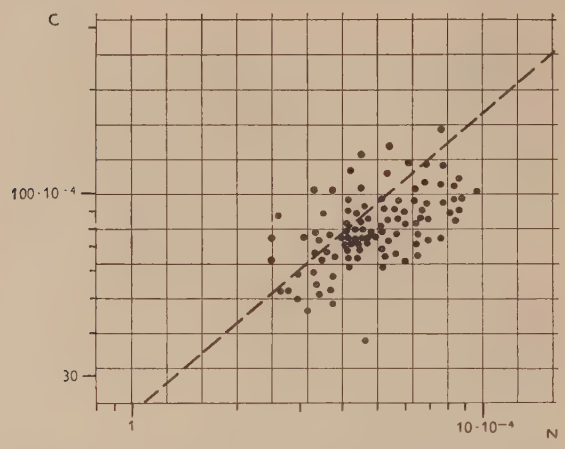

Fig. 2.46.4. Relation between carbon and nitrogen concentrations in core 46. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits.

higher (5 %), and the rate of accumulation of calcium carbonate somewhat lower (7 %) in core 46 than in core 45. As a result the clay members are thicker than in the latter core. The normal eupelagic sequence is well reproduced, although there is some doubt with regard to the exact position of some substages and of the culmination of stage 5.

The distribution of organic matter is regarded as normal and a post-depositional decrease in nitrogen can be traced. The distribution of phosphorus is abnormally irregular and remains unexplained. Well preserved digging structures and faecal pellets are abundant.

.1 Calcium carbonate. The vertical distribution of carbonate is very similar to the corresponding distribution in core 45. The average concentration is, however, lower which is partly due to a slightly higher rate of accumulation of non-calcareous matter (144 g/cm² since stage 11 in core 46 and 137 g/cm² during the same time in core 45), and partly to the decreased accumulation of calcareous matter (96 g/cm² since stage 11 in core 46 and 103 g/cm² during the same time in core 45). The carbonate stratification is in good agreement with the normal eupelagic sequence in spite of the higher rate of accumulation of minerogenous matter in core 46 (approx. 125—130 % of the corresponding average rate in core 60, calculated from stage 11).

.4 Organic matter. The correlation between carbon and nitrogen (fig. 2.46.4) is fairly good and the carbon values scatter less than in core 45. There is a marked increase of the ratio C/N with increasing depth, mainly due to the downwards decreasing average nitrogen concentration. This effect, which is believed to be post-depositional, obscures the otherwise fairly good negative correlation between carbonate and nitrogen. A significant deviation from this correlation is formed by the maximum in organic matter found in the carbonate-rich stage 2. This feature is typical for most normal eupelagic deposits of the East and East Central Equatorial Pacific.

.5 Phosphorus. The distribution of phosphorus in core 46 is puzzling, as the correlation

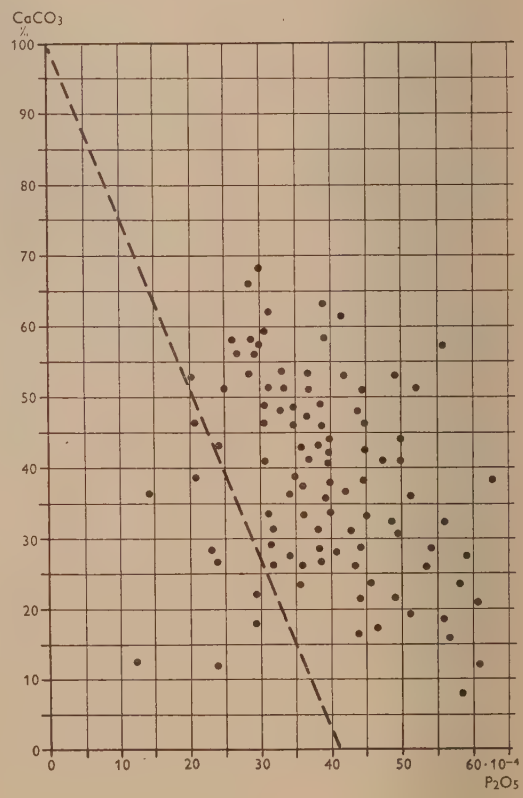

Fig. 2.46.5. Relation between concentration of phosphorus and concentration of calcium carbonate in core 46. The dashed line corresponds to the estimated eupelagic average.

with carbonate is much poorer than could be expected (fig. 2.46.5). The reason for the greatly increased dispersion of the values is not seen. Large scale secondary levelling of the phosphate concentration by migration does not appear probable in this case, as visible structures indicating such migration are not more frequent here than in core 45. Additional investigation is necessary to explain the abnormal type of distribution of phosphorus.

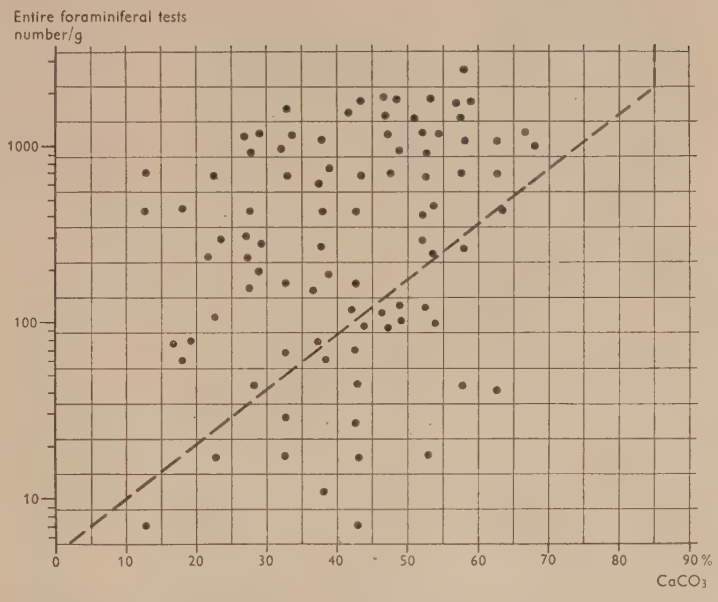

Fig. 2.46.7.1. Relation between concentration of entire foramineral tests and percentage of calcium carbonate.
The dashed line illustrates the average eupelagic conditions.

.6 Colour and pattern. With regard to colour and pattern this core is very similar to core 45, and all the general features of the description given in § 2.45.6 are applicable here. Thus the colour distribution as well as the frequency of manganese micronodules indicates a secondary displacement of manganese towards the surface of the sediment still more marked than in core 45.

Reduction bodies are frequent and, with regard to the occurence of structures filled with loose or consolidated material or with faecal pellets, core 46 surpasses core 45. The clay balls described in 2.45.6 are also here frequently associated with typical digging structures of worm hole type. An exceptionally long vertical part of a worm hole extended from 422 to 447 cm. The upper, slightly funnel-shaped end terminated in a layer rich in clay balls of the type referred to above. At 445 cm the channel bent off and disappeared from the core. The channel cut over two diffuse colour limits at 433 and 443 cm and the light colour of the filling material (2 ca) indicated reducing conditions. A layer of the type 40—873 x was found at 607 cm and another at 519 cm.

.7 Foraminifera. The trend of the concentration curve for planktonic foraminifera (pl. 2.46) generally coincides with the trend of the carbonate concentration curve but on account of frequent singular deviations and of changes in the proportionality between the two factors their correlation is still poorer than in core 45 (fig. 2.46.7.1.). As in the latter core, samples abnormally rich in foraminifera with regard to the content of calcium carbonate are abundant. The reason for this might be sought in the fact that on the dissolution of carbonate which is apparently active in both cores, the fine grained calcium carbonate was, owing to its greater surface per unit weight and its higher solubility dissolved first and the entire foraminiferal tests were thus enriched. Discrepancies between calcium carbonate and foraminiferal concentrations are especially frequent below stage 10.

The foraminiferal integrity index decreases on the average downwards as in core 45, which might indicate an additional slow, postdepositional dissolution of the tests.

The concentration of benthonic foraminifera is normal or slightly too low with regard to the concentration of planktonic foraminifera (pl 2.46, fig. 2.46.7.2). The dispersion of the

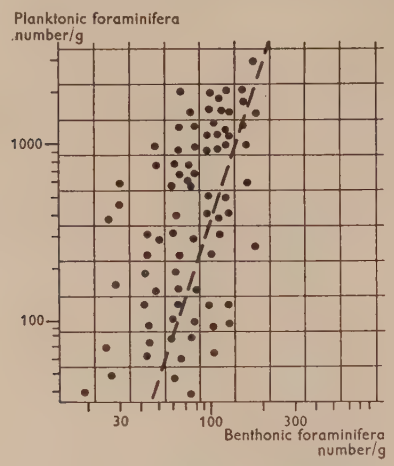

Fig. 2.46.7.2. Relation between concentration of entire tests of planktonic and benthonic foraminifera in core 46. The dashed line corresponds to the estimated eupelagic regression (§ 1.7.2).

The distribution is similar to that found in core 45 (fig. 2.45.7.2), although the enrichment of benthonic tests in very low foraminiferal concentrations is not as marked as in this core.

values is approximately the same as in core 45 (fig. 2.45.7.2).

The inferred original composition of the foraminiferal plankton fauna as well as the secondary changes brought about by fragmentation and dissolution are highly similar in core 45 and 46. Thus the percentage of *Globorotalia* is still correlated with, but too low in view of the concentration of plankton (fig. 2.46.7.3). The lack of *Globorotalia* dominance in stage 7 and the existence of such dominance in substage 8.3, both notable features of the stratigraphy of core 45, are repeated in core 46 (pl. 2.46).

.8 Radiolaria. The concentration of radiolaria is low, and no stratigraphical conclusions can be drawn from their distribution. Although extensively corroded skeletons are frequent, specimens in an apparently perfect state of preservation were also observed. This might possibly be due to partial redeposition of radiolaria as has been demonstrated by W. Riedel (1951). If this is so the source beds of the redeposited radiolaria are probably not pre-Pleistocene as no fossil forms were found at a preliminary scrutiny kindly undertaken by Mr Riedel.

.9 Diatoms. The frustules are extensively corroded and the size distribution analysis of *Coscinodiscus nodulifer* is, therefore, not possible.

.10 — .11 Other fossils. Rock fragments and mineral grains. Besides the fossil remains referred to above, sponge spicules (max. 80/g), »mollusc fragments» (24), fish teeth (24) and spines of echinoderms (max. 8/g) were found.

Manganese micronodules are most frequent in the upper beds (max. 70/g). Glass and other mineral grains do not exceed 10/g.

.12 Diagenesis. Below the very loose surface deposit the strength of the sediment rises with irregular variations down to approx. 5 m. Below this level the strength varies around a constant or very slowly rising value. The salinity is normal to high with regard to

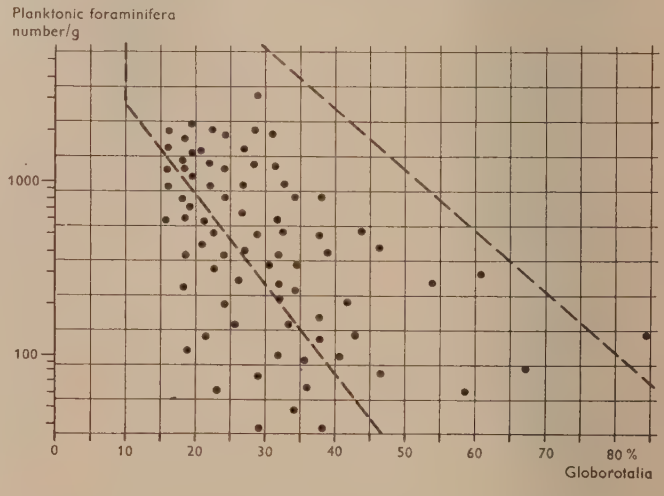

Fig. 2.46.7.3. Relation between concentration of entire tests of planktonic foraminifera and planktonic faunal percentage of *Globorotalia menardii + tumida*. The guide lines coincide roughly with the eupelagic equiprobability curve 0.05, i. e. the probability of occurence of a eupelagic sample outside these boundaries is less than 10 percent.

The normal correlation between concentration of planktonic foraminifera and percentage of *Globorotalia menardii + tumida* is strongly counteracted by selective dissolution, which tends to decrease the original percentage of *Globorotalia*.

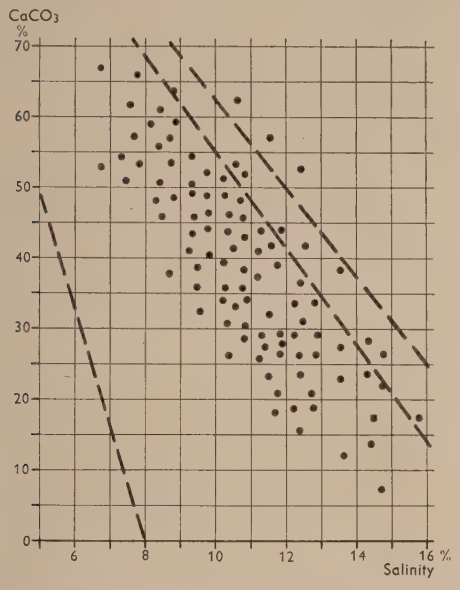

Fig. 2.46.12. Relation between calcium carbonate content and salinity in core 46. The dashed lines correspond to lines A, B and C in fig. 1.12.2.1 and 1.12.2.2.

the carbonate content and the distribution of the values (fig. 2.46.12) is very similar to that found in core 45 (fig. 2.45.12).

.13 Stratigraphy. Only a few centimeters of the top of the core appear to be lost as the vertical distribution of calcium carbonate and foraminifera indicate the presence of at least the lower part of substage 1.2 (Recent). The agreement of the stratigraphy with core 45 and with the normal equifacial eupelagic sequence is very good. As in core 45, substages are believed to be recognized in stages 3, 8 and 9. The subdivision of the two latter stages is, however, regarded, as somewhat more ambiguous than in core 45. The distribution of foraminifera indicates that the culmination of stage 5 is located approx. 50 cm lower than is made probable by the concentration of calcium carbonate. However, the concentration minimum of foraminifera and the percentage maxima of *Globorotalia* and benthonic foraminifera at 500—530 cm are all caused by an abnormally far-reaching fragmentation. The carbonate distribution is therefore believed to give the best representation of the stratigraphically significant accumulation conditions in this case. The identification of the basal layers in core 45 with stage 13 is corroborated by the conditions found in core 46.

Core 47

East Pacific Ridge

(North Equatorial carbonate facies)

Station no. 70.

Lat. 9° 14′ N, *Long.* 109° 39′ W.

Depth 3 560 m.

Core length 971 cm.

Topography: The core was raised from the slope of a 1 000 m high seamount, presumably a volcano (fig. 2.47.0).

Abstract of interpretation. Core 47 consists of chalk ooze with a few marl ooze layers. The topography of the surroundings, the lack of normal stratification, and the faunal composition make probable that redeposition strongly influences the sequence. The redeposited material appears partly to be of shallow water origin. This is understandable as high peaks rise from the East Pacific Ridge in this area, some of them extending above or close to the surface of the sea (Clipperton Island and Germaine Bank).

The manganese present is to an unusually high degree concentrated to macroscopic nodules. As a result the blackness of the deposit is comparatively low and the hue yellowish.

Due to the locally influenced rate and

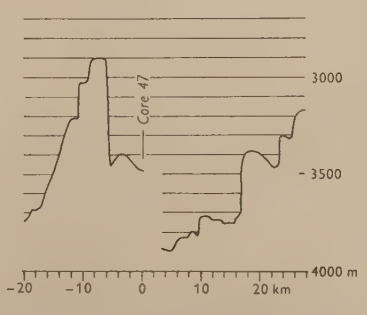

Fig. 2.47.0. Bottom topography in the vicinity of the station of core 47. Redrawn from Koczy (contribution to vol. IV).

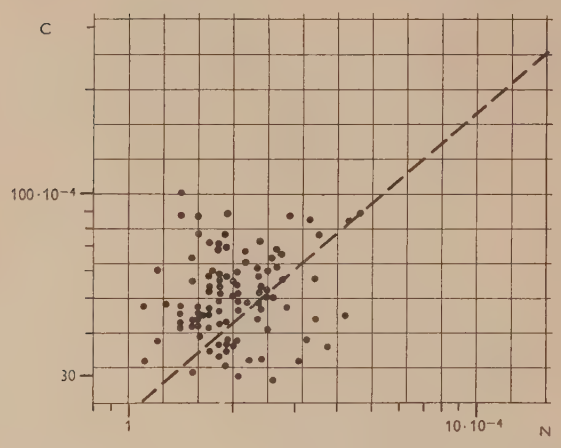

Fig. 2.47.4. Relation between carbon and nitrogen concentrations in core 47. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits.

quality of deposition the normal stratigraphical features are almost completely obscured and the core cannot, therefore, be correlated.

.1 Calcium carbonate. Globigerina chalk ooze predominates and only a few layers of marl ooze occur. One of these consists partially of globorotalia marl ooze and might retain traces of an original stratigraphical feature.

.4 Organic matter. The correlation between carbon and nitrogen is very poor (fig. 2.47.4). No effect of ageing can be traced in the vertical distribution of nitrogen (pl. 2.47). As compared with other East Pacific Ridge cores, core 47 is poor in organic matter.

.5 Phosphorus. The correlation with the carbonate content (fig. 2.47.5) is obvious but there is a considerable dispersion of the values. The slope of the regression line is less steep than normal, indicating an abnormally high (approx. $80 \cdot 10^{-4}$) content of phosphorus in the minerogenous matter. Still higher values (approx. $120 \cdot 10^{-4}$) are indicated by the abnormal group of samples from the marl ooze layer at the bottom of the core (pl. 2.47 and fig. 2.47.5).

.6 Colour and pattern. The colour of the deposit varies between light brown and yellowish brown. Especially the beds below 6 m are rich

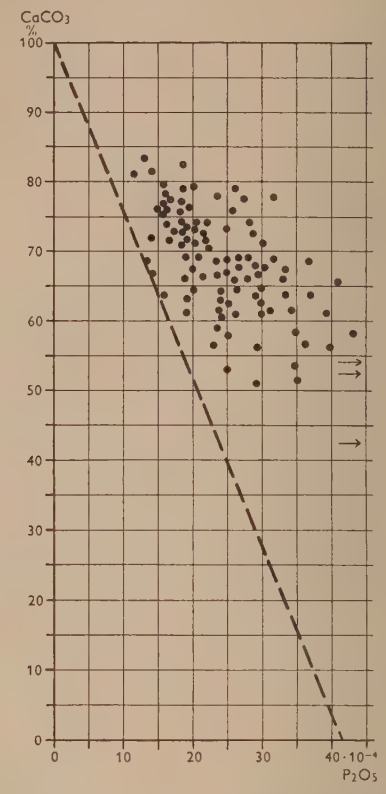

Fig. 2.47.5. Relation between concentration of phosphorus and concentration of calcium carbonate in core 47. Arrows indicate samples with a higher content of phosphorus than $45 \cdot 10^{-4}$ P_2O_5. The dashed line corresponds to the estimated eupelagic average.

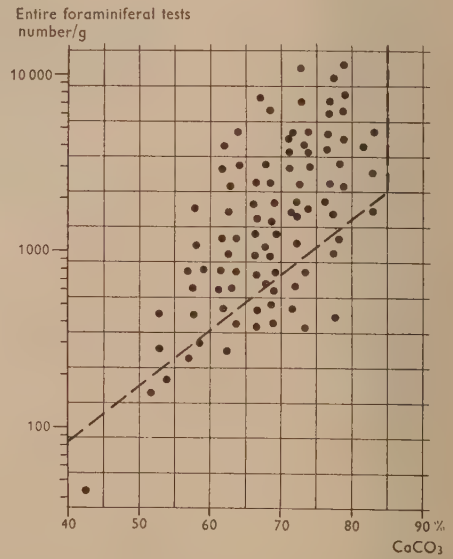

Fig. 2.47.7.1. Relation between concentration of entire foramineral tests and percentage of calcium carbonate. The dashed line illustrates the average eupelagic conditions.

The steepness of the regression indicates that the changes in concentration of entire tests are largely due to changes in the extent of fragmentation.

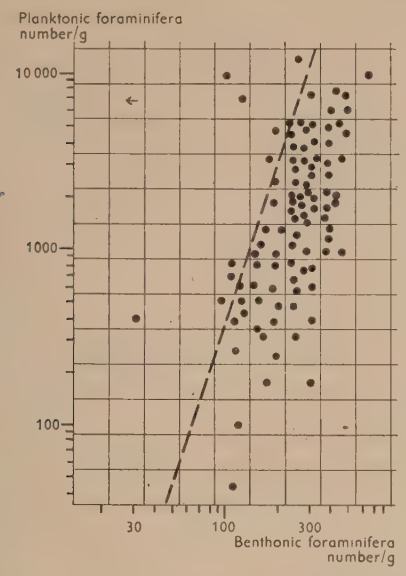

Fig. 2.47.7.2. Relation between concentration of entire tests of planktonic and benthonic foraminifera in core 47. The dashed line corresponds to the estimated eupelagic regression (§ 1.7.2).

The abnormally high concentration of benthos is believed to be caused by an admixture of shallow water forms.

in irregular or eyeshaped reduction structures. Neither were any unquestionable burrowing structures found nor any indication of slumping.

.7 Foraminifera. The average concentration of foraminifera is high (pl. 2.47), the correlation with calcium carbonate steeper than normal (fig. 2.47.7.1), and the percentage of benthos abnormally high (pl.2.47 and fig. 2.47.7.2). According to F. Brotzen[1]), some of the benthonic species indicate shallow water origin, thus giving additional evidence of redeposition. The relationships between relative distribution of faunal elements and concentration of planktonic foraminifera (pl. 2.47 and fig. 2.47.7.3) are believed to be influenced by mixing and by dissolution in the last or an earlier cycle of deposition.

.8 Radiolaria. The radiolaria are often corroded and, especially in the lower bed, in a poor state of preservation. The highest concentrations are found in the intermediate beds (pl. 2.47).

.9 Diatoms. A marked maximum of large specimens of *Coscinodiscus nodulifer* is present between 250 and 350 cm. It is highly improbable that this typical size distribution could be retained in a redispersed and redeposited sediment or brought about by selective sedimentation. The *Coscinodiscus* distribution found in the upper four meter bed of the core is therefore supposed mainly to be original. On account of the lack of other correlatable features it is, however, difficult to judge the stratigraphical significance of the size distribution of *Coscinodiscus nodulifer* in this case.

.11 Rock fragments and mineral grains. Glass, palagonite and manganese micronodules are found in most of the samples; the nodules being sometimes abundant (448 cm and 653 cm). A big rounded nodule, 2 cm in diameter, was found suspended in the sediment at 211 cm. The nucleus consisted of a piece of weathered glass and the surrounding sedi-

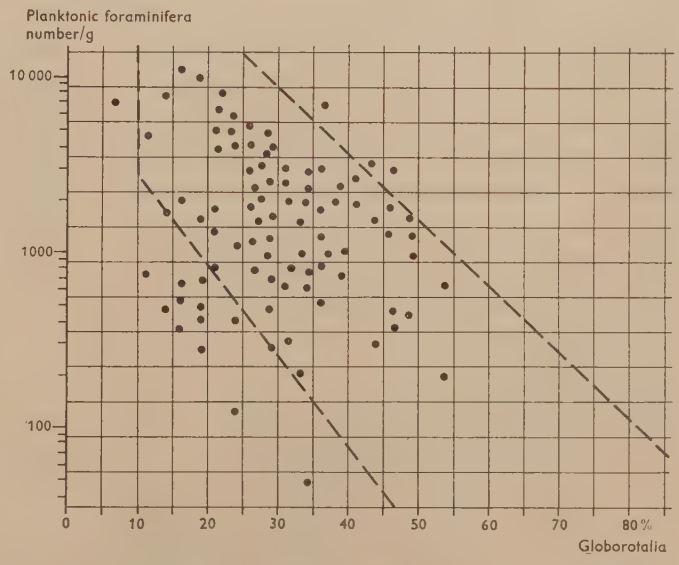

Fig. 2.47.7.3. Relation between concentration of entire tests of planktonic foraminifera and planktonic faunal percentage of *Globorotalia menardii + tumida*. The guide lines coincide roughly with the eupelagic equiprobability curve 0.05, i. e. the probability of occurrence of a eupelagic sample outside these boundaries is less than 10 percent.

[1]) Personal communications.

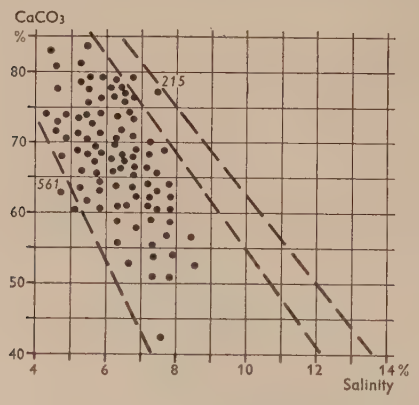

Fig. 2.47.12. Relation between calcium carbonate content and salinity in core 47. The dashed lines correspond to lines A, B and C in fig. 1.12.2.1 and 1.12.2.2.

ment, 205—220 cm, was lighter (3 ge-ic) than the overlying (4 lg-ng) and underlying (4 ng—5 ni) deposit. Smaller nodules were found at 42 and 421 cm.

.12 Diagenesis. The vertical distribution of strength is regarded as normal. The abnormally low values at 157 and 280 cm are both connected to levels of mechanical disturbance of the deposit caused by the coring device. Layers indicating a locally increased induration occur preferably in the lower beds. Most salinity values are normal or low with regard to the carbonate content (fig. 2.47.12). Corrosion of radiolaria and foraminifera is frequently observed and recrystallized foraminifera are abundant.

.13 Stratigraphy. As mentioned in § 2.47.9 there is a marked frequency maximum of big specimens of *Coscinodiscus nodulifer* extending from 350 to 250 cm. This frequency distribution certainly retains primary features. Further the marked maximum of benthos and the dominance of *Globorotalia* in the marl ooze layer 515—434 cm and in the underlying 35 cm chalk ooze layer indicate that this bed might have ecological and thus stratigraphical significance. The lack of general resemblance to the normal eupelagic sequence, however, makes it impossible to apply the stratigraphical indications and to correlate core 47.

Core 48

East Pacific Ridge

(North Equatorial silica facies)

Station no. 73.
Lat. 11° 25′ N, *Long.* 113° 48′ W.
Depth 4 085 m.
Core length 695 cm.
Topography: No record.

Abstract of interpretation. Core 48 consists of greyish yellow to dark brown siliceous clay overlying a rapidly deposited basal bed. This is built up by a basal layer of gravel of superficially weathered volcanic glass, further by clay, glass breccia in clay and clay with a great amount of suspended grains of weathered glass. The clay beds above approx. 590 cm are believed to be normally deposited. The lower part of this stratigraphically normal clay is rich in phosphate, manganese nodules, and reduction bodies. This and the overlying beds are supposed to be members of time-rock units recognizable all over the North Equatorial Clay Area and possibly also in other oceans. The surface of the core probably represents a surface of abrasion, non-deposition or of abnormally slow deposition, as a large conchoidal manganese nodule was found growing in it. The structure and the salinity of the deposit indicate the presence of exceptionally great amounts of colloidal silica.

.1 Calcium carbonate. The content of calcium carbonate is mostly near zero and exceeds 5 % in one case only.

.4 Organic matter. The concentration of carbon is high and the content of nitrogen normal for a pelagic clay. There is a marked gradual decrease in the nitrogen concentration from the top to the bottom. This decrease is most probably due to secondary changes. Even if particular regard is taken to this feature the correlation C to N is, as in most pelagic clays investigated, very poor (fig. 2.48—50.4).

.5 Phosphorus. There is a marked stratification with regard to phosphorus. As is seen from fig. 2.48.5 there are at least two different groups of samples, one with a fairly high average phosphate content of $60—70 \cdot 10^{-4}$ P_2O_5 and one or several with very high phosphate values (above $90 \cdot 10^{-4}$). The very high values are all located in the bed 550—390 cm, overlying the basal beds. These, which for reasons quoted below are supposed to have been rapidly deposited, are poor in phosphorus (approx. $15—40 \cdot 10^{-4}$). The unaltered glass is not believed to be the source of the phosphorus as it displays a very low content ($9 \cdot 10^{-4}$) which appears to be to a high degree retained at weathering. A secondary enrichment to $15 \cdot 10^{-4}$ is thus found in the yellow, weathered rim of the glass.

The possible origin of the stratification with regard to phosphorus is discussed in § 1.5.2.

.6 Colour and pattern. The clay is yellowish grey to dark brown. The changes in colour do not appear to be connected with any of the other properties investigated. The frequency of reduction bodies is low in the upper 250 cm, increases between 250 and 348 cm, and is high down to 580 cm. The limit at 348 cm is sharp. Most of the reduction bodies are massive and only a few mm in diameter, but horse shoe and eye structures are also frequent. An irregular colour limit occurs at 573 cm. Several sharp and inclined boundaries are found in the basal, glass bearing bed. The deposit constituting the top meter of the core has a typical smell resembling methyl alcohol.

.7 Foraminifera. Entire tests mostly of benthonic and sometimes of arenaceous forms are found only sporadically except below 596 cm where the occurrences are most probably due to redeposition. Fragments of foraminifera are comparatively frequent in the top 1/2 m.

.8 Radiolaria. The concentration of radiolaria decreases downwards, which is thought to be caused by secondary dissolution. The maximum at 630 cm is considered to be caused by redeposition.

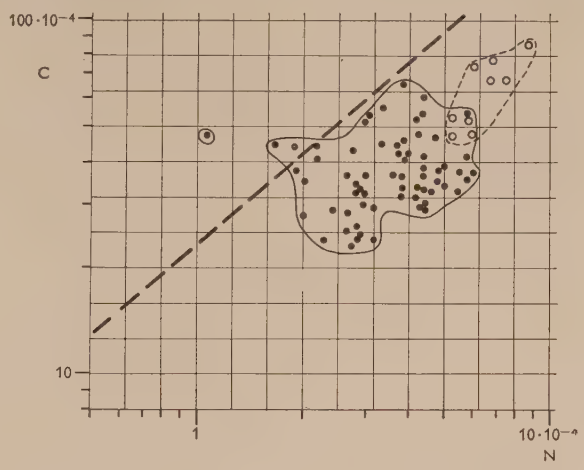

Fig. 2.48—50.4. Relation between carbon and nitrogen concentrations in core 48 (filled circles) and 50 (open circles). The dashed line corresponds to the estimated average of the calcareous East Pacific deposits.

.10 Other fossils. (pl. 2.48) Small quantities of fish teeth occur regularly. The concentration is increased to 4—5/g between 482 and 542 cm (cf fig. 2.48.10.1). Sponge spicules like radiolaria decrease downwards, probably due to dissolution (cf fig. 2.48.10.2). The »mollusc fragments» are distributed in much the same way as the foraminiferal fragments. Three different frequency maxima are present (fig. 2.48.10.3), one in very low, one in comparatively high, and one most pronounced in intermediate concentrations.

.11 Mineral grains and rock fragments. The concentration of palagonite and glass is usually less than 10 grains $> 150\ \mu$/g except in the bed 460—330 cm where the content is twice or three times as high and in the basal bed where the maximum 433 grains/g is attained. Most of these grains are smaller than 1 mm but numerous larger fragments were observed below 590 cm suspended in the sediment and randomly oriented. A four cm long splinter was found in an inclined position at 653—650 cm. The deposit between 670 and 678 cm is a breccia of glass and palagonite fragments of

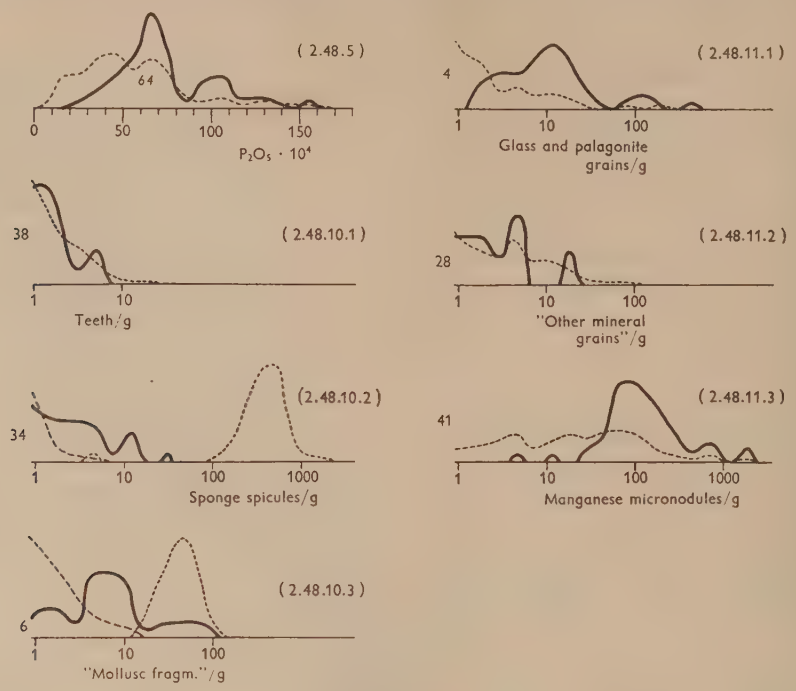

Fig. 2.48.5—10—11. Frequency distribution of phosphorus, »other fossils», rock fragments and mineral grains in core 48.

The dashed reference curve in the *phosphorus* diagram refers to the average distribution in the North Equatorial clay area. The surface below the curve (full line) corresponds to 100 % of the samples of core 48 and the number of samples is indicated in this surface.

In the distribution diagram of *fish teeth and annelide jaws* the dashed reference curve refers to the average distribution in the North Equatorial clay area. The number to the left of the diagram indicates the percentage of samples with a content lower than 1.

The dashed reference curves in the frequency diagram of *sponge spicules* refer to the distributions in core 57 (right dashed curve and isolated small maximum) and in core 51 (left dashed curve). The number to the left of the diagram indicates the percentage of samples with a content lower than 1.

In the frequency diagram of *»mollusc fragments»* the dashed reference curves and the numbers to the left have the same significance as in the diagram of sponge spicules.

The dashed reference curves of the diagram *glass and palagonite*, the diagram *»other mineral grains»* and the diagram *manganese micronodules* refer to the average distributions in the North Equatorial clay area. The significance of the left number is the same as indicated above.

The class interval is in the case of phosphorus 10^{-3} P_2O_5 and in the case of the other properties the intervals correspond to the groups in the grouping system 20 indicated in table 1.0.3. The numbers of the figures are in brackets.

sizes up to 1 cm and embedded in clay. The basal five cm layer consists entirely of gravel of black glass. All glass fragments found have a weathered rim, approx. 0.5 mm thick in the large fragments and up to 1 mm in the small, entirely weathered grains. The weathered glass (palagonite) is reddish yellow and has a varying refractive index, lower than the index (1.62) of the black, unaltered glass. The glass apparently contains gases or water in solid solution as it decrepitates and rises at heating.

On the whole the deposit is very rich in manganese nodules (fig. 2.48.11.3 and pl. 2.48). Exceptionally high concentrations ($>1\,000$ nodules/g) are found in the deposit overlying the basal beds rich in weathering glass. It is not known whether this maximum is associated with a corresponding maximum in concentration of manganese or if the conditions found only express a changed state of dispersion of the authigenic manganese minerals present in the deposit.

A conchoidal manganese nodule with an approximate diameter of 1 cm was found at the upper surface of the core. Another nodule, a few millimeters in size, was found at 269 cm. There is no change in the colour of the sediment around the nodules.

»Other mineral grains» occur in concentrations up to 20/g and are not markedly correlated with the rock fragments.

.12 Diagenesis. The salinity decreases downwards, indicating that the increased strength is at least partly due to expulsion of water. As is seen from pl. 2.48 the increase in strength with increasing depth is abnormally high in core 48. In spite of the high average strength, the salinity (pl. 2.48 and fig. 2.48.12.2) and water content are also very high if compared with the cores 51 and 54 (cf. § 1.12.2). The sediment in core 48 thus appears to be rich in water and at the same time to have a high strength. These abnormal properties are probably responsible for the peculiar tough, rubberlike consistence of the deposit. The ultimate reason for these anomalies may be a high concentration of silica gel, an assumption which is corroborated by the fact that the deposit turns extremely hard and tough when dry and by other conditions referred to in § 1.12.2. The stratum 664—590 cm is rich in glass, very loose and has a high percentage of chlorides (water). 680—664 cm containing the glass breccia is hard (no measurement) and the clay overlying the basal glass gravel again looser. The layer 597—598 cm has a low salinity in spite of the decreased strength. A fracture due to core sampling is present at 600 cm but it is difficult to explain the greatly lowered strength by this fact, and the conditions found in this stratum thus remain unexplained.

.13 Stratigraphy. Core 48 was apparently raised from an area of volcanic activity and the basal bed was deposited very rapidly, possibly in connection with one or several eruptions. There is no evidence that the beds above 690 cm were deposited with abnormal rapidity. The distribution of manganese and phosphorus, probably indicates a fairly high rate of accumulation of these elements in the intermediate beds and a somewhat decreased rate in the upper ones. This general sequence, except the basal slumping, is met with in almost all pelagic clay cores included in this investigation and appears to occur also in the Atlantic Ocean. By reasons of analogy the main features of core 48 are therefore regarded as correlatable.

Core 50 A

East Eupelagic Area

(North Equatorial clay facies)

Station no. 76.

Lat. 13° 20′ N, *Long.* 117° 58′ W.

Depth 4 248 m.

Core length 47 cm.

Topography: Regular bottom with a few shield-formed elevations, the highest with an altitude of approx. 25 m and a base length of approx. 1 000 m.

Abstract. Core 50 A consists of brown, stratified clay, apparently of Recent and Late Pleistocene age.

.1 Calcium carbonate. Only in one case exceeding 2 %.

.4 Organic matter. The relationship C to N (fig. 2.48—50.4) indicates conditions like those found in core 48. The content of organic matter is, however, higher and the correlation C to N better than in this core. Both carbon and nitrogen decrease strongly from the surface down to 23 cm.

.5 Phosphorus. The concentration is low and varies between 19 and $30 \cdot 10^{-4}$.

.6 Colour and pattern. The colour of the deposit is greyish to yellowish brown with a stratification shown in pl. 2.50. Above appr. 12 cm the sediment is homogenous and below this level has a mottled appearance.

.7 Foraminifera. Concentrations up to 9/g occur. Most specimens found are benthonic and arenaceous.

.8 Radiolaria. The concentrations vary between 800 and a few thousand and are regarded as normal for Recent and Late Pleistocene deposits in the North Equatorial clay area.

.10 Other fossils. (pl. 2.50) »Mollusc fragments» are restricted to the lower part of the core. Fish teeth were found in only one sample. Sponge spicules are fairly frequent.

.11 Mineral grains and rock fragments. Manganese micronodules are most frequent in the upper part of the core. A conchoidal manganese nodule approx. 1 cm in diameter was found at the surface of the deposit. The lower side was irregular and the upper smooth and rounded surface was protruding into the water. The content of glass, palagonite and other mineral grains is low to intermediate.

.12 Diagenesis. It is difficult to compare core 50 A with other cores because of its shortness. The salinity, however, indicates (fig. 1.12.2.3) that this sediment takes an intermediate position between core 48 and 51.

.13 Stratigraphy. As long as the possibilities of a stratigraphical detail subdivision of pelagic clays are lacking it is difficult to draw any stratigraphical conclusions from the sequence represented by core 50 A. By the courtesy of Professor Hans Pettersson, the samples were analyzed with regard to their content of radium.[1]) The results (pl. 2.50 col. Ra) demonstrate that the normal decay curve is not reproduced in this core and no absolute age determination can thus be based upon the radium distribution in the present case. The results, however, corroborate the conclusion drawn from the state of preservation of radiolaria and organic matter, viz. that the top of the core represents Recent and Late Pleistocene.

[1]) Analyst: V. Kröll.

Core 51

East Eupelagic Area

(North Equatorial clay facies)

Station no. 78.

Lat. 15° 40′ N, *Long.* 123° 21′ W.

Depth 4 300 m.

Length of core 969 cm.

Topography: No record.

Abstract of interpretation. Core 51 consists of light, greyish yellow clay, partly coloured dark by manganese and iron compounds. Considerable amounts of colloidal silica appear to be present as the siliceous fossils have to a great extent been dissolved within the sediment. Mud-eater traces are frequent. The induration increases very regularly with depth. The stratigraphical units P 1—6 are recognized. The top one or few centimeters of P 1 might be missing.

.1 Calcium carbonate. The concentration varies between zero and a few percent.

.4 Organic matter. The carbon content is low and decreases slightly downwards. The nitrogen content is high in comparison with the carbon, and the relationship between these two elements (fig. 2.51—52.4) is, therefore, typical for eupelagic clay deposits (cf. chapter 1.4). Two abnormally low nitrogen values occur,

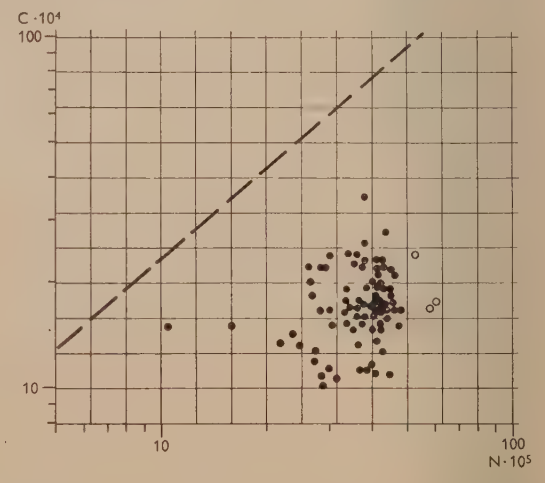

Fig. 2.51—52.4. Relation between carbon and nitrogen concentrations in core 51 (filled circles) and 52 (open circles). The dashed line corresponds to the estimated average of the calcareous East Pacific deposits.

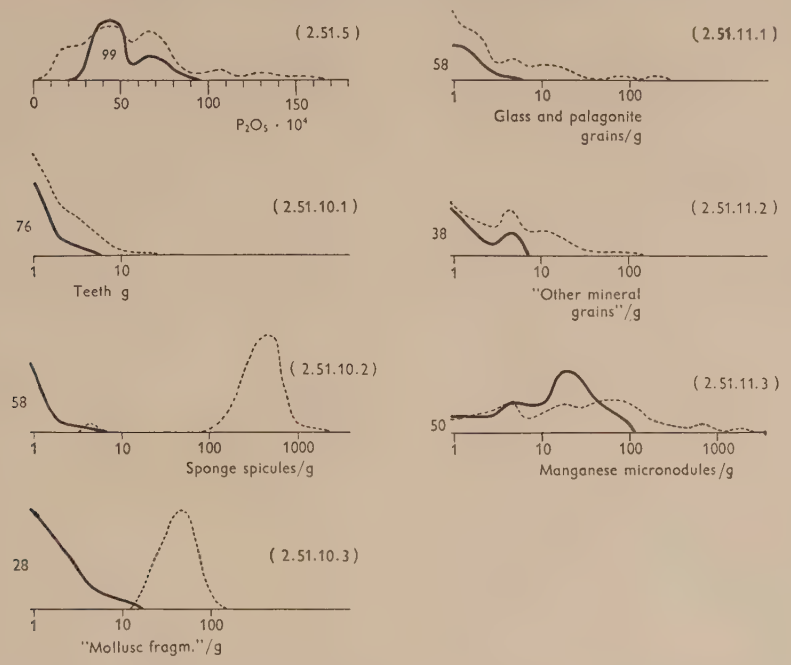

Fig. 2.51.5—10—11. Frequency distribution of phosphorus, »other fossils», rock fragments and mineral grains in core 51. Details with regard to the construction of the diagrams are given in the caption of fig. 2.48.5—10—11. The numbers of the figures are in brackets.

one at 214 cm, the other at 232 cm. Their significance is not known. Below 5 m the nitrogen concentration gradually decreases downwards. This decrease is believed to be a diagenetical effect.

.5 Phosphorus. The frequency distribution of phosphorus concentration values (fig. 2.51.5) is bimodal with one maximum in intermediate and one in intermediate to high concentrations. Stratigraphically the intermediate concentrations are restricted to the upper 4.5 m bed and to the bed 885—825 cm (Pl and P5). The higher concentrations are found below 885 cm and between 825 and 500 cm (P4 and P2).

.6 Colour and pattern. The beds below 505 cm are yellowish brown with only one intercalated light layer (581—580 cm). Alternating dark and light colours follow to 462 cm where the sediment turns light greyish yellow. Above 405 cm the deposit is again darker with alternating light layers of varying frequency. A dark brown layer occurs between 378 and 368 cm. The dark pigment was investigated at several levels of the core and was found to consist of finely divided manganese and iron compounds.

All boundaries are reworked and diffused, apparently by bottom scavengers. Open cavities were found at 95 and 6 cm. Typical reduction bodies, especially eye structures, are found between 800 and 680 cm. The pattern is illustrated by pl 2.6.2

.7 Foraminifera. Entire tests and fragments occur only in low concentrations (1—3/g).

.8 Radiolaria. Concentrations exceeding 10/g occur in the uppermost 50 cm bed only. The deficiency in siliceous fossils is believed partly to be due to dissolution as all the specimens found are corroded.

.10 Other fossils. Small numbers of fish teeth occur in most samples. Sponge spicules are, like radiolaria, affected by secondary dissolution and their frequency thus decreases downwards. The distribution of »mollusc fragments» is possibly also affected by post-depositional dissolution.

.11 *Mineral grains and rock fragments.* Glass, palagonite and other mineral grains occur in small quantities in most samples. Comparatively large quantities of manganese micronodules (> 20/g) are found in the beds P2, P4, and P6 and their frequencies are fairly well correlated with the concentration of phosphorus. Three singular maxima occur in the upper bed P1 viz. at 176, 156, and 122 cm but these are not accompanied by an increased phosphate content of the sediment. One possible explanation of the differences in the manganese nodule—phosphorus relationship is that the high content of nodules in the beds P2, P4, and P6 are primary features, due to an increased rate of accumulation of manganese, whereas the maxima in the bed P1 might be caused by postdepositional migration.

.12 *Diagenesis.* There is a good correlation between strength and depth (pl. 2.51.), approximately identical with that found in core 54 pl. 2.54). As the real top of the column is thought to be missing it is difficult to tell whether the relationship between depth and logarithm of strength is linear or curved. The deviation to the left (pl. 2.51) of the samples from the present top of core 51 might be caused by the slight mechanical disturbance, (not mixing) of the deposit which appears to be caused by the coring device. On account of these facts the relationship mentioned has been calculated preliminarily as a straight line for comparative use.

The correlation between strength and salinity is poor, and the increased strength does not appear to be caused chiefly by expulsion of water on the compression of the lower beds. The lowered salinity of the members P2, P4, and P6 is therefore regarded mainly as a primary textural feature. The fact that the salinity of the member P5 is not as high as in P1 and that there is a slight decrease downwards in P1, however, indicates that expulsion of water might be taking place to some extent.

.13 *Stratigraphy.* The stratigraphical interpretation of core 51 is based upon the vertical distribution of phosphorus (§ 1.5.2). The upper 500 cm bed is believed to correspond to the time-rock unit P1, 500—590 to P2, 590—620 to P3, 620—820 to P4, 820—880 to P5, and below 880 to P6. Late Pleistocene is present according to the state of preservation of siliceous fossils but to judge from the vertical distribution of organic matter a few centimeters of the top may have been lost at sampling.

Core 52

East Eupelagic Area

(North Equatorial clay facies)

Station no. 79.

Lat. 16° 35′ N, *Long.* 124° 48′ W.

Depth 4 230 m.

Core length 32 cm.

Topography: The bottom profile was recorded approx. 10 km before the station and was found to be level. Close to the station, however, a 400 m high seamount (presumably a group of volcanoes) suddenly appeared (fig. 2.52.0) and the core was raised at the foot of this mount. On the course again after the station this change between comparatively vast plains and mountainous areas was recorded several times in appr. 60 km.

Abstract of interpretation. Core 52 consists of a fossil-bearing, greyish brown clay rich in glass and palagonite and containing two manganese crusts. The crusts are formed by rounded nodules rich in clay, glass and palagonite and loosely or strongly cemented to-

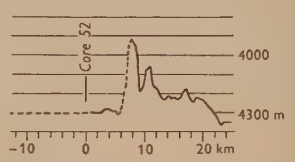

Fig. 2.52.0. Bottom topography in the vicinity of the station of core 52. Redrawn from Koczy (contribution to vol IV).

gether. The upper crust was originally covered by a few centimeters of clay, washed off at sampling. The lower one is possibly not in its correct stratigraphical position but might be identical with the upper one and was in that case sampled at the second lowering of the piston corer.

.1 Calcium carbonate. Below 2 %.

(All chemical and biological analysis values refer to the intercalated clay if nothing else is indicated).

.4 Organic matter. The composition is of the normal pelagic clay type, the nitrogen content being high and the concentration of carbon low (fig. 2.51—52.4).

.5 Phosphorus. The phosphorus content of the clay is intermediate to high ($63 \cdot 10^{-4}$ P_2O_5) whereas the manganese crusts are poor ($28 \cdot 10^{-4}$ P_2O_5) in phosphate.

.6 Colour and pattern. The colour of the clay between the black manganese crusts is greyish brown (4 lg—ng) with a lighter reduction structure (4 ea) between 16 and 14 cm. The manganese crusts consist of clayey, crumbling nodules of all sizes up to 1.5 cm in diameter. In the upper crust (6—0 cm) the aggregates are not as strongly cemented together as in the lower one (32—27 cm).

.7 Foraminifera. No entire tests or fragments were found.

.8 Radiolaria. The intercalated clay is very poor in radiolaria and the specimens present are extensively corroded.

.10 Other fossils. Fish teeth were found in concentrations up to 6/g clay, which is regarded as high. The concentration of sponge spicules varies from intermediate to low. »Mollusc fragment» concentrations are intermediate.

.11 Mineral grains and rock fragments. The clay is rich in palagonite and glass, especially close to the upper manganese crust. The apparent lowering of the palagonite-glass content in the intermediate part of the intercalated clay is due to the increased amount of manganese micronodules of which a great number contain palagonite grains as a nucleus.

After dissolving with hydrochloric acid the manganese oxides of the big nodules of the crusts, concentric shells of loosely cemented clay, remain. The clay forms a porous network and includes sponge spicules, fragments of fish bones, phillipsite and considerable amounts of glass.

.13 Stratigraphy. Due to the circumstances at sampling there are two possible interpretations of the sequence found. When the piston corer was released, the lowering of the tension of the cable was not very marked. The corer was therefore raised approx. 15 m and again lowered whereupon it toppled over and apparently fell on the bottom. The mouthpiece was deformed against the manganese crust. The sequence of the material in the corer was as follows: 32—27 cm, strongly cemented manganese crust, 27—6 cm, clay; 6—0 cm loosely cemented manganese crust. The upper manganese crust was originally covered by a layer of clay which was, however, washed away owing to the unfavourable sampling conditions. To judge from the clay marks on the weights of the corer this clay layer did not exceed a few cm in thickness.

The possibility cannot be excluded that there is on the bottom only one manganese crust overlying clay, and that the basal crust of the core was sampled at the second lowering of the piston corer. The observed lithological differences between the upper and lower crusts might well be due to lateral variations in the structure and composition of one single crust. The loose surface clay is likely to have been pushed aside at the second lowering, and it is not very probable that much of it is present above the lower crust of the core.

Core 53

East Eupelagic Area

(Present North Equatorial clay facies)

Station no. 81.

Lat. 15° 34′ N. *Long.* 127° 11′ W.

Depth 4 725 m.

Length of core 348 cm.

Topography: The depth was continuously recorded NNE and S of the station. The bottom was found to be undulating (fig. 2.53.0) generally with relative altitudes not exceeding 70 meters and with slopes seldom exceeding 5 %. At the station there was a depression, approx. 80 m deep, from which the short core 53 B was raised. The long core, 53, originates from the edge of the bordering plain.

Abstract of interpretation. Core 53 represents a truncated sequence consisting of Tertiary chalk ooze, marl ooze and clay. The missing top is believed to correspond to at least 10 m of Pleistocene and Late Pliocene clays and an unknown thickness of older calcareous deposits. It is not known with certainty whether the truncation was caused by slumping or by gradual current abrasion. Petrological evidence favours the latter alternative which is, however, made less probable by hydrological considerations.

The calcium carbonate and foraminiferal relationships indicate depositional conditions markedly deviating from those typical for Pleistocene sequences. Thus the fragmentation and corrosion of foraminifera is less pronounced, which is believed to be an effect of the higher temperature of the Tertiary deep water as compared with the Pleistocene.[1]) A few zones are comparatively rich in volcanic glass and allogenic mineral grains.

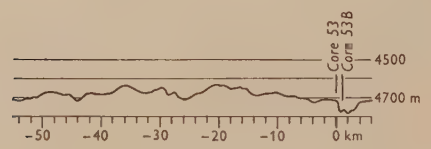

Fig. 2.53.0. Bottom topography in the vicinity of the station of core 53. Redrawn from Koczy (contribution to vol. IV).

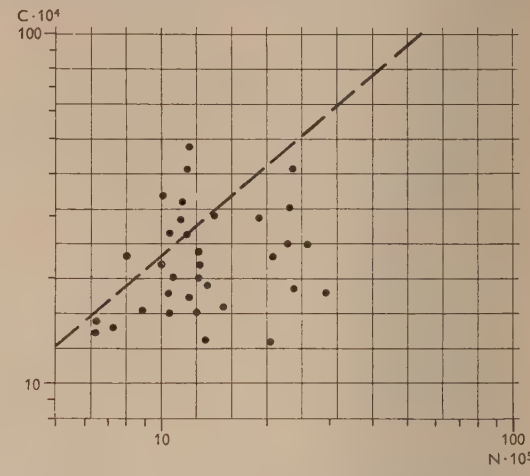

Fig. 2.53.4. Relation between carbon and nitrogen concentrations in core 53. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits.

The upper chalk and marl ooze bed is comparatively rich in manganese micronodules. The diagenesis has proceeded very far as compared with other Pacific deposits investigated.

Core 53 A, raised from a depression close to core 53, consists of a loose, light clay, free from carbonates and fossils $> 150\,\mu$ except radiolaria. This material is believed to be entirely or partly derived from the abraded deposits.

.1 Calcium carbonate. The variations in concentration of calcium carbonate are great, the poorest clay layer containing only 1 % and the top layer of chalk ooze 62 % $CaCO_3$. The carbonate is present mainly in the form of entire and broken tests of foraminifera and recrystallized fragments, some still recognizable as foraminiferal, others impossible to identify on account of the diagenetical changes. Core 53 A contains no carbonate.

.4 Organic matter. The deposit is very poor in organic matter and the distribution of values in the C/N diagram (fig. 2.53.4) forms a transition from the type of the calcareous oozes to that of pelagic clays. Curiously enough,

[1]) See also footnote to § 2.57.0.

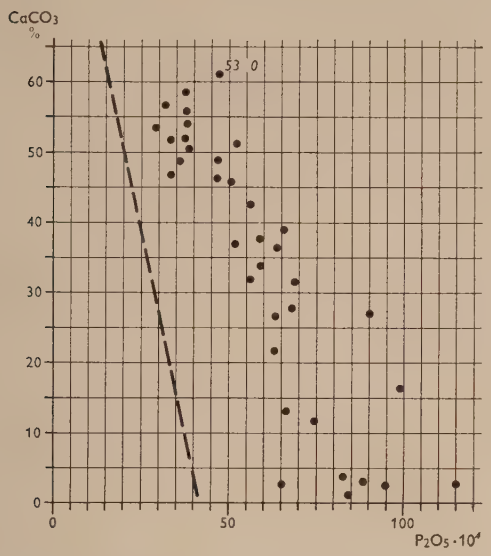

Fig. 2.53.5. Relation between calcium carbonate and phosphorus concentrations in core 53 (calcareous Tertiary). The deposit is abnormally rich in phosphorus as compared to the Pleistocene eupelagic sediments, represented by the dashed regression line.

the value pairs most resembling those typical for normal pelagic clays (high in nitrogen, low in carbon) are found in the upper chalk and marl ooze bed.

.5 *Phosphorus.* The correlation between phosphorus and carbonate is good (fig. 2.53.5) but the increase of phosphorus with decreasing carbonate content is stronger than in normal eupelagic cores. The possible reasons for this are discussed in chapter 1.5. The top sample (0) is abnormally rich in phosphorus, possibly because the surface has been in contact with sea water for an abnormally long time. Core 53 A is very poor in phosphorus.

.6 *Colour and pattern.* The carbonate rich parts of the core are yellowish-greyish brown and the clayey parts dark brown. Mud-eater traces and reduction bodies are frequent. A structure of the type 40—873 x was found at 332 cm in a slightly inclined position. This is one of the few cases where a structure of this kind terminates within the core, thereby proving not to be a real layer but a prismatic body of limited horizontal extension. Core 53 A is greyish brown.

.7 *Foraminifera.* In the Pleistocene pelagic marl and marly chalk oozes of the East Pacific the number of entire foraminifera is appr. doubled when the carbonate content is increased with 10 % (chapter 1.7). This is due to the simultaneous increase of rate of sedimentation of foraminifera and decrease of the rate of fragmentation. In core 53, on the other hand, the concentration of entire tests is less rapidly increasing with the carbonate concentration (fig. 2.53.7.1). This probably depends on the conditions of fragmentation in this Tertiary deposit, the integrity index being high and not very strongly varying (pl. 2.53 and fig. 2.53.7.2) in comparison with normal eupelagic Pleistocene sequences. The deviating conditions of fragmentation in their turn are certainly to some part due to the high percentage of benthos in core 53, the benthonic test structures being more resistant to destruction than the planktonic ones. Thin sections of the foraminifera demonstrate that corrosion is not very extensive in core 53 as compared with normal eupelagic Pleistocene

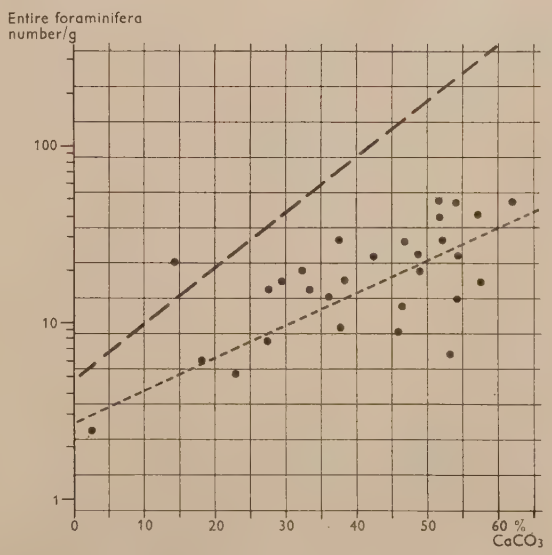

Fig. 2.53.7.1. Relation between concentration of entire foraminiferal tests and of calcium carbonate in core 53 (dotted line). The dashed line corresponds to the Pleistocene average. In core 53 the average amount of entire tests is doubled at each increase of the calcium carbonate concentration with appr. 16 %.

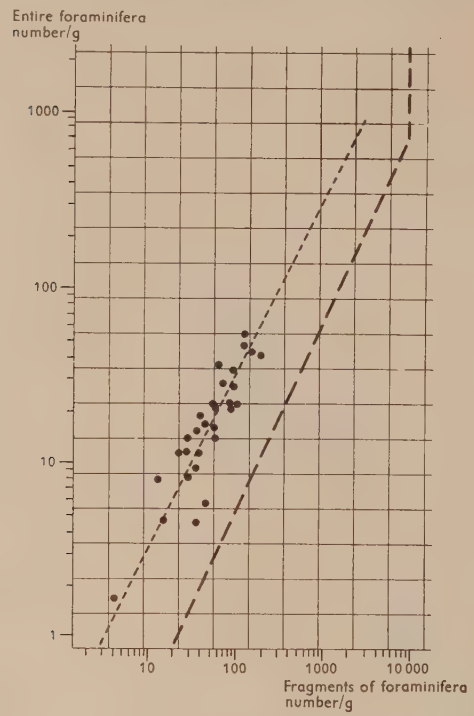

Fig. 2.53.7.2. Relation between entire foraminiferal tests and fragments of tests in core 53. The dashed line corresponds to the estimated Pleistocene eupelagic average. The dotted regression line corresponds to the relationship $f = 3e$, where f is the concentration of fragments and e is the concentration of entire tests.

deposits of corresponding carbonate content. This effect certainly contributes to the deviations from the normal type of the relationships conc. entire tests/conc. calcium carbonate and conc. entire tests/conc. fragments. The comparatively low corrosion is believed to be due to a higher average temperature of the deep water of the ocean during Pre-Pleistocene time.

The planktonic species represented by entire tests belong to 100 % to the genus *Globigerina*. Among the fragments, however, *Globorotalia* is well represented. The percentage of benthos is high and in all levels exceeds 100 %. According to Brotzen, fossil (Tertiary) species occur among the benthonic foraminifera The closer age relationships of this core will be treated in a special paper by Brotzen. Core 53 A does not contain foraminifera or foraminiferal fragments.

.8 Radiolaria. The concentration of both radiolaria and other siliceous fossils is very low. Those present are not very strongly corroded and the low concentration is therefore believed mainly to be a primary feature. The reason for the increased concentration of radiolaria at 337 cm is not known.

Core 53 A is high in radiolaria as compared to core 53.

.10 Other fossils. Fish teeth are fairly frequent, sponge spicules scarce, and »mollusc fragments» very frequent. Echinoid spines occur sporadically.

.11 Mineral grains and rock fragments. The frequency distribution of manganese nodules (fig. 2.53.11.3) is bimodal with one maximum in low, and one in intermediate to high concentrations. The low values are all found below 90 cm (pl. 2.53) and most of the high concentrations in the uppermost part of the core.

Glass, palagonite and »other mineral grains» are low except in the surface layer and the levels 100 and 162 cm. The maxima in »other mineral grains» at the two latter levels are partly due to unweathered glass, occurring together with anisotropic (e. g. feldspar) and opaque minerals (e. g. magnetite).

.12 Diagenesis. The strength confirms the high age of the deposit and amounts already in the top of the core to values normally found only below 10 m. The lower clay member in particular is strongly indurated. The deposit has attained a slaty structure with approximately vertical, irregular surfaces of preferred cleavage. The salinity is low with regard to the carbonate content (fig. 2.53.12). Corrosion is not very pronounced but the recrystallization of calcareous structures is far-reaching.

.13 Stratigraphy. The Tertiary age of the deposit, the state of induration, and the bottom topography confirm that core 53 is confined upwards by a surface of abrasion or non-deposition. It is difficult to judge which of these two

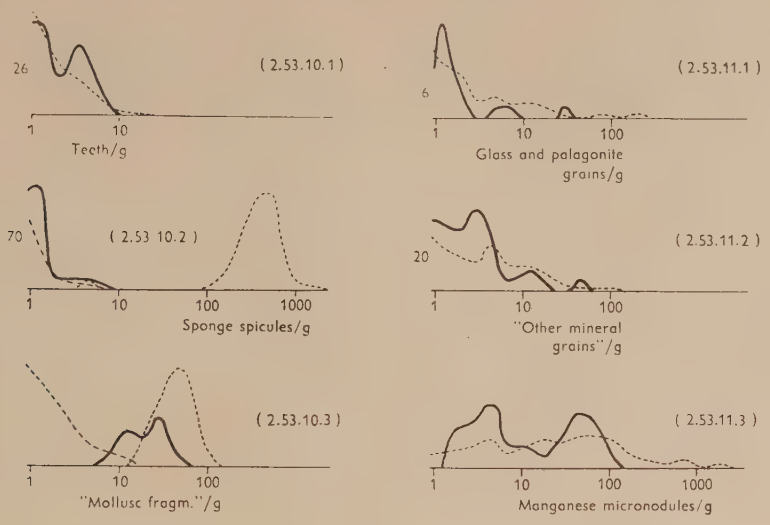

Fig. 2.53.10—11. Frequency distribution of »other fossils», rock fragments, and mineral grains in core 53. Details with regard to the construction of the diagrams are given in the caption of fig. 2.48.5—10—11. The numbers of the figures are in brackets.

alternatives is the right one. The abrasion alternative is favoured by the fact that no manganese crust has developed, that the carbonate content of the surface deposit has not been considerably lowered by secondary dissolution, and that the surface is not strewn with fish remains. Under such conditions core 53 A might represent the abraded material or the finest grades of it deposited in the depression next to core 53. If this is so, the composition of core 53A indicates that the abrasion and redeposition were slow enough to allow complete dissolution of the fine-grained calcium carbonate fraction. Another possibility is that the original top beds have fairly recently slumped off from the locality 53 and that core 53 A represents the upper, carbonate-free part of the slumped cover. The high strength of the deposit in core 53, however, contradicts this interpretation.

The reason for assuming non-deposition as an alternative explanation to abrasion is that bottom currents strong enough to be capable of extensive abrasion have generally not been considered as existing in the Pacific (SVERDRUP, e. a. 1946, p. 752). The mechanism which caused the uncovering of the Tertiary subsurface deposits in core 53 must therefore be regarded as not quite clear. The fact that only a few centimeters of sediment entered the short tube (core 53 A) indicates that the loose surface layer here is thin and covers a more strongly indurated deposit.

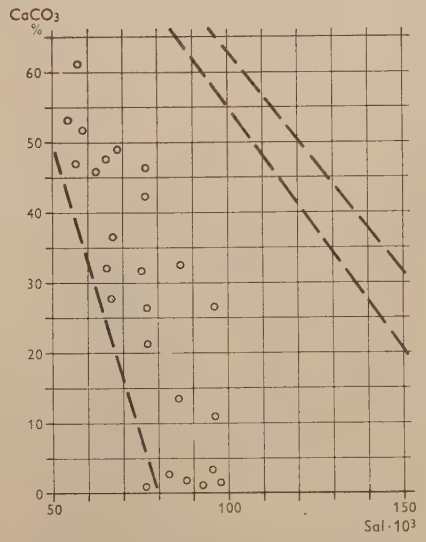

Fig. 2.53.12. Relation between calcium carbonate content and salinity in core 53. The dashed lines correspond to lines A, B and C in fig. 1.12.2.1 and 1.12.2.2.

Core 54

East Eupelagic Area

(North Equatorial clay facies)

Station no. 83.

Lat. 13° 17′ N. *Long.* 127° 25′ W.

Depth 4 800 m.

Length of core 971 cm.

Topography: The landscape is of the same undulating type as that surrounding station 81, although gradients and altitudes give an impression of somewhat less maturity around core 54. The core was raised from a depression bordering a shield formed elevation 240 m high and with an approximate slope of 2 %.

Abstract of interpretation. Core 54 consists of a very light coloured yellow clay partly coloured dark by manganese and ferric compounds. The concentration of siliceous fossils is subject to strong changes which are at least partly due to secondary dissolution. The distribution of salinity is of interest from a regional point of view. There is a conspicuous stratification with regard to the concentration of phosphorus and this stratification is used as a basis for a tentative correlation with other clay cores. Further evidence is, however, necessary before the stratigraphical subdivision suggested can be confirmed.

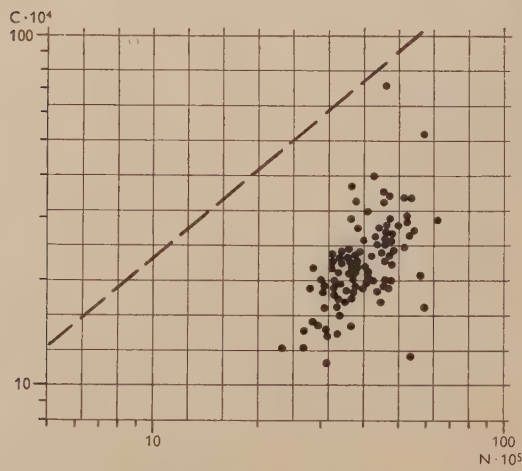

Fig. 2.54.4. Relation between carbon and nitrogen concentrations in core 54. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits.

.1 Calcium carbonate. The carbonate content is mostly close to zero. Zones with slightly increased concentrations occur but these do not exceed 3 %.

.4 Organic matter. The carbon — nitrogen relationship is typical for eupelagic clays (fig. 2.54.4). Thus the nitrogen content is high and has a narrower range of variation than the carbon content. The correlation between the two properties is fairly good. The effect of ageing is conspicuous both in carbon and nitrogen.

The amount of nitrogen present in the form of ammonium compounds was investigated in the upper part of the core (dashed curve in col. N, pl. 2.54, scale at the lower end of the column) and was found to be approx. 12 % of the total amount.

.5 Phosphorus. The phosphorus distribution is very similar to that in core 51. Thus the frequency distribution (fig. 2.54.5) is bimodal and the bimodality has a stratigraphical significance, the high values being restricted to the members P 2 and P4 (pl. 2.54). The average phosphorus content in each of the two frequency groups is considerably lower in core 54 (15 and $50 \cdot 10^{-4}$ P_2O_5) than in core 51 (42 and 66 $\cdot 10^{-4}$ P_2O_5). The distribution of phosphorus is believed to be the most reliable basis available at present for the correlation of core 54.

.6 Colour and pattern. With regard to colour there is a very marked stratification in core 54. Thus the clay base, which is whitish yellow, (3ca—ea) is at certain levels coloured blackish brown by finely divided manganese and ferric compounds. The most pronounced dark coloration occurs in the basal 20 cm bed, between 860 cm and 630 cm and between 500 cm and 315 cm. There is, therefore, fairly good agreement between manganese coloration and abundance of phosphorus.

Digging structures and reduction bodies are frequent throughout the column and are most easy to trace in the dark coloured beds, due to the marked colour contrasts (pl. 2.6.2—3.)

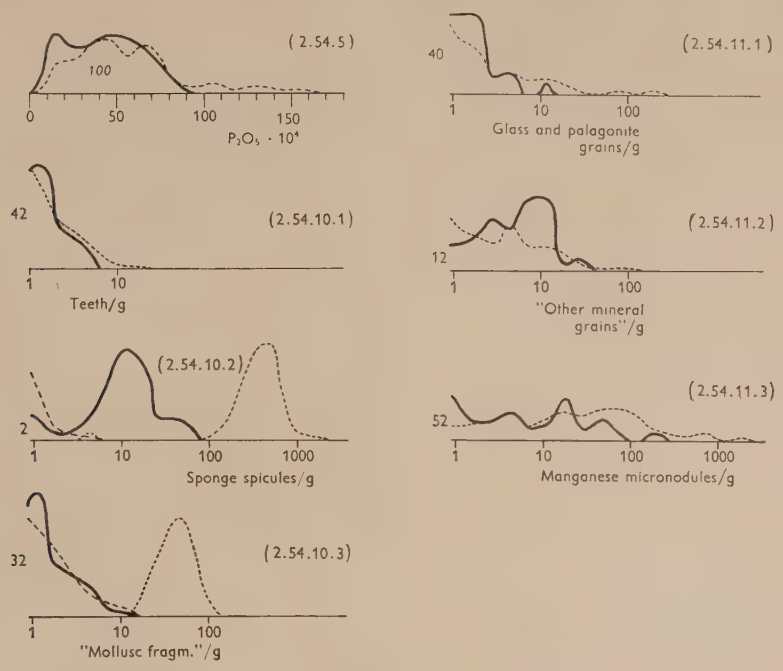

Fig. 2.54.5—10—11. Frequency distribution of phosphorus, »other fossils», rock fragments, and mineral grains in core 54. Details with regard to the construction of the diagrams are given in the caption of fig. 2.48.5—10—11. The numbers of the figures are in brackets.

.7 Foraminifera. Entire tests and fragments occur only in very low concentrations.

.8 Radiolaria. The radiolarian skeletons are extensively corroded and the vertical distribution found (pl. 2.54) is very probably a product of secondary dissolution. The occurrence of an isolated maximum in the basal beds indicates either that the original concentration was very high in this zone or that the skeletal remains were for some reason better preserved here than in the intermediate beds. It is difficult to interpret the present distribution in terms of rate of deposition of radiolaria as long as the rate of dissolution cannot be checked quantitatively.

.10 Other fossils. Fish teeth occur only in amounts of 4/g or less. The highest concentrations are most frequent in the intermediate beds. Sponge spicules are frequent and on account of their higher resistance to dissolution, their concentration in the intermediate beds is not as strongly decreased as the concentration of radiolaria. The samples from these beds thus form an abnormal group in the correlation diagram sponge spicules/radiolaria (fig. 1.10.2.2).

.11 Mineral grains and rock fragments. Small amounts of palagonite, glass, and »other mineral grains» occur in most samples. Fairly distinct maxima are found at the base of the core, at 596 cm, 190 cm, 48 cm, and at the surface. The concentration of manganese micronodules is strongly varying; from a few to more than 200/g. There is hardly any correlation with the phosphorus concentration or with the amount of finely divided manganese oxides as reflected by the blackness of the deposit.

.12 Diagenesis. The increase of strength with depth is normal. With regard to the distribution of salinity this core forms a transition from the North Equatorial eupelagic clay type, (represented by 51 and 52) to the North Equatorial siliceous ooze type (represented by the core series 55, 56, and 57) (cf § 1.12.2). Thus the main part of the salinity values are still very low especially in the lower

beds but intermediate values occur in the uppermost 4 m layer. The quantitative correlation salinity-depth and salinity-strength is very poor.

.13 Stratigraphy. Of the properties investigated only the phosphorus concentration appears to be usable for correlation purposes. For this reason, only the gross features can be correlated and the correlation has to be regarded as tentative. If the subdivision indicated in pl 2.54, col P_2O_5, is correct it might be noted that the member P1 is appr. 18 % thinner in core 54 than in core 51.

Core 55

East Eupelagic Area

(North Equatorial clay — silica facies)

Station no. 85.

Lat. 11° 30′ N. *Long.* 127° 37′ W.

Depth 4 916 m.

Length of core 273 cm.

Topography: The core was raised from a broad (approx. 10 km) and shallow (approx. 150 m) depression (fig. 2.55.0) close to a minor elevation (approx. 40 m high).

Abstract of interpretation. Core 55 displays many similarities to core 54 also with regard to the stratification. In spite of the shortness of the core, the member P2 appears to have been sampled. The short length is probably due to distortion caused by an accident at sampling. The transition from North Equatorial clay facies to North Equatorial silica facies can be traced in the distribution of foraminifera, radiolaria, sponge spicules, »mollusc fragments» and salinity.

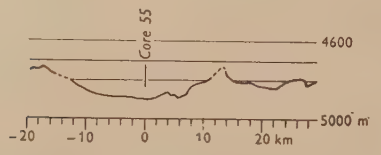

Fig. 2.55.0. Bottom topography in the vicinity of the station of core 55. Redrawn from Koczy (contribution to vol IV).

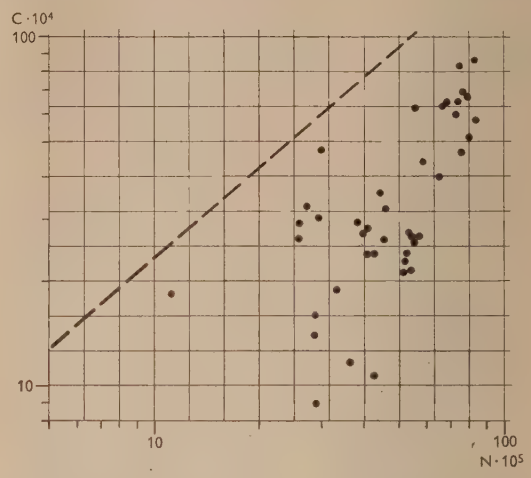

Fig. 2.55.4. Relation between carbon and nitrogen concentrations in core 55. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits.

.1 Calcium carbonate. The carbonate content is usually close to zero. An occasional rise to 5.5 % occurs at 220 cm.

.4 Organic matter. The distribution of carbon and nitrogen is typical for eupelagic clays (fig 2.55.4). Thus the carbon content is generally subjected to stronger variations than the nitrogen content and the ageing effect is marked. Two abnormally low nitrogen values occur in the basal bed.

.5 Phosphorus. The normal stratigraphical distribution of phosphorus is repeated in core 55, the top bed (here 200—0 cm) being relatively poor in phosphate and resting upon a series of alternating phosphate-poor and phosphate-rich deposits. Only the top phosphate-rich bed (P2) appears to have been sampled in core 55. As in cores 51 and 54 a subordinate maximum can be traced in the member P1.

.6 Colour and pattern. As in core 54 the supposed member P1 has mainly a whitish-yellow colour and the phosphate-rich bed is coloured blackish-brown by finely divided manganese and ferric compounds. Digging structures are frequent but reduction bodies are not as numerous as in cores 51 and 54. (pl. 2.6.2 and 2.6.3).

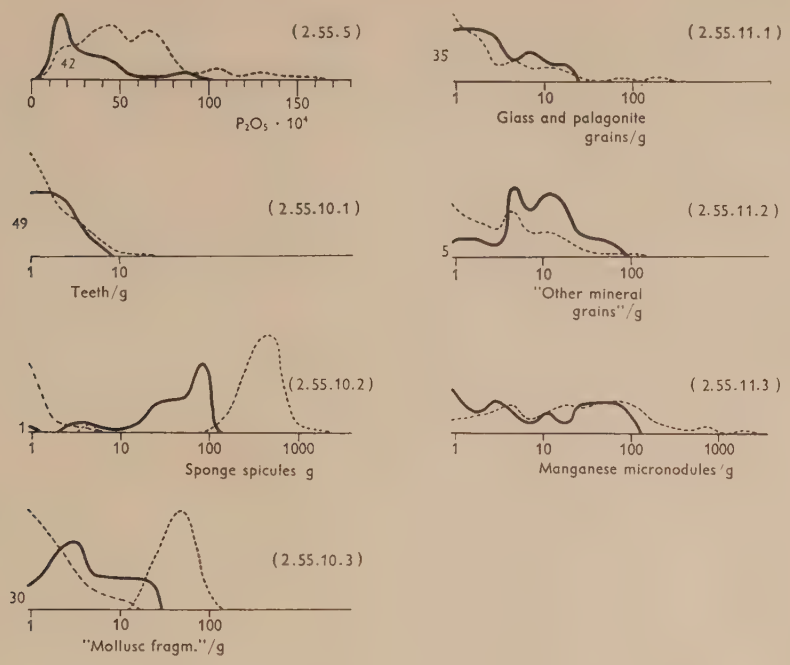

Fig. 2.55.5—10—11. Frequency distribution of phosphorus, »other fossils», rock fragments, and mineral grains in core 55. Details with regard to the construction of the diagrams are given in the caption of fig. 2.48.5—10—11. The numbers of the figures are in brackets.

.7 *Foraminifera.* Comparatively high numbers of entire tests and fragments occur. Most specimens found are benthonic and several are arenaceous.

.8 *Radiolaria.* As in core 54 the concentration of radiolaria is high in the top bed but decreases rapidly downwards. The observations of corrosion indicate that this decrease is at least partly caused by secondary dissolution. The relative importance of changes in the rate of deposition is not known.

.10 *Other fossils.* Fish teeth occur in small to moderate amounts. The concentration of sponge remains is high and in accordance with the facies (transition from North Equatorial clay facies with very low concentrations to North Equatorial silica facies with very high concentrations). As in the radiolaria the frequency of sponge spicules decreases downwards, partly due to dissolution and possibly to an unknown degree due to ecological changes. The facies transition represented by core 55 can also be traced in the frequency distribution of »mollusc fragments» (fig 2.55.10.3). Low concentration values are not as frequent as in core 54 and intermediate to high values occur. Stratigraphically these are mostly restricted to the bed 100—30 cm.

.11 *Mineral grains and rock fragments.* Fairly high concentrations of glass, palagonite and anisotropic allogenic mineral grains $> 150\ \mu$ occur and the stratigraphical distribution indicates that the supply has varied considerably with time. The distribution of manganese micronodules is fairly closely connected with the frequency of allogenic rock fragments and mineral grains and the nodules are supposed partly to originate from manganese, released at the weathering of these fragments.

.12 *Diagenesis.* Both strength and salinity change abnormally rapidly with depth in the deposit. Thus the upper 80 cm bed is abnormally loose and rich in water (measured quantitatively as chloride) and strongly indurated layers occur in the lower part of the core. In this lower part there is no correlation be-

tween salinity and strength. The reason for the abnormal diagenetical conditions are not known. The extensive induration of some layers might be caused by cementing silica dissolved from radiolaria as strongly corroded specimens were observed mostly to be filled and surrounded by cemented clay aggregates.

.13 Stratigraphy. The short Phleger coring tube was attached to the Kullenberg piston corer during sampling. Owing to this arrangement the piston corer appears to have been released while on the way towards the bottom. In spite of this, full depth of penetration (10 m) was attained and the short tube corer was filled (46 cm). However, only a 273 cm column entered the piston corer. The composition of the top layer of this column as compared with the short core 55 B makes probable that approximately 50 cm of the top but not much more is entirely missing in core 55. It is therefore necessary to assume that the beds penetrated by the piston corer are not represented in their correct proportions in core 55. This assumption is corroborated by the vertical distribution of phosphorus, the member P1 being abnormally short.

Core 56

East Eupelagic Area

(North Equatorial silica facies)

Station no. 86.

Lat. 9° 50′ N. *Long.* 128° 13′ W.

Depth 4 629 m.

Length of core 102 cm.

Topography: The core was raised from an approx. 5 km broad plateau close to the border where it slopes into a shallow depression, approx. 100 m deep and 10 km wide. The landscape is of the normal general type found in the East Eupelagic area with a smoothly undulating surface and usually very gentle slopes (< 2 %).

Abstract of interpretation. Core 56 is of great interest as it gives an example of a complete erosional cycle, beginning and ending with deposition and including a considerable time gap caused by non-deposition and erosion. The calcareous basal layer is assumed to be of Tertiary age and is followed conformably by a phosphatic clay member P (4 + 2 x) more and more slowly deposited (as inferred from the manganese cementation) and confined by an erosional surface. Upon the unconformity rests a loose, light coloured clay, poor in phosphate and possibly 2 m thick. This bed was distorted at sampling and only 7—9 cm of it are present in the core. The real top appears to be present and to be of Recent or Subrecent age. Diagenesis has proceeded very far in the clay member P (4 + 2 x).

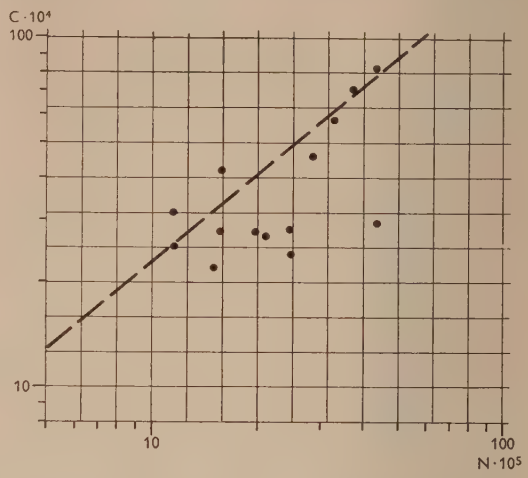

Fig. 2.56.4. Relation between carbon and nitrogen concentrations in core 56. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits.

.1 Calcium carbonate. With the exception of the basal layer the core is practically free from carbonate. In the basal layer there is a sudden increase to 21 %, indicating that Lower Cenozoic beds have been reached.

.4 Organic matter. The carbon-nitrogen relationship (fig. 2.56.4) resembles very much that found in core 53 (Calcareous Lower Cenozoic, fig. 2.53.4) and in core 57 (including Calcareous Lower Cenozoic, fig. 2.57.4).

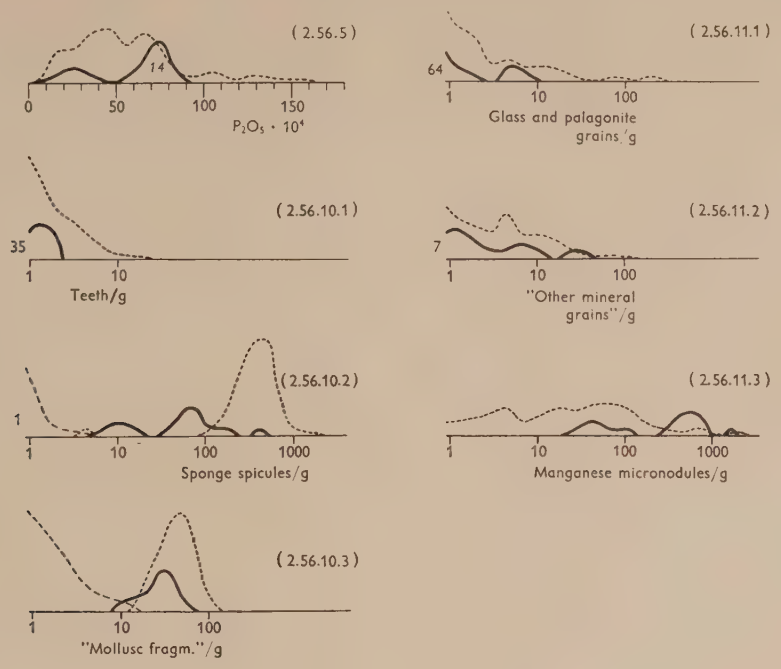

Fig. 2.56.5—10—11. Frequency distribution of phosphorus, »other fossils», rock fragments, and mineral grains in core 56. Details with regard to the construction of the diagrams are given in the caption of fig. 2.48.5—10—11. The numbers of the figures are in brackets.

.5 Phosphorus. Above the unconformity at 7—9 cm the phosphorus content is very low and below the unconformity it is intermediate to high and decreasing in the basal bed. The calcareous basal layer indicates that the phosphorus-rich bed P (4 + 2x) is older than P 4 and probably equivalent to the phosphatic clay member overlying the Tertiary marl ooze in core 57.

.6 Colour and pattern. A most interesting feature is the unconformity at 7—9 cm. The discontinuity surface (pl. 2.6.3 and 2.6.8) is irregular and the overlying, loose light-coloured sediment has a composition and texture deviating from the underlying dark and strongly indurated deposit. This is brittle and has attained a partly well developed vertically oriented lamination. The calcareous basal layer has a somewhat lighter colour than the overlying bed.

.7 Foraminifera. The entire tests and fragments found in the basal layer mostly originate from benthonic forms. It is hoped that the age relationships will be more closely elucidated by an investigation of the foraminifera, carried out by Dr. F. Brotzen.

.8 Radiolaria. The top layer above the unconformity contains a few thousand radiolaria ($> 150\ \mu$)/g and these are as a rule well preserved. In the lower beds the specimens found are extensively corroded and the concentration is strongly decreased but rises again in the basal bed. It is not known whether this increase is entirely due to ecological changes or to the preserving influence of the calcium carbonate.

.10 Other fossils. Fish teeth occur in small numbers only. The concentration of sponge spicules varies from low immediately below the unconformity to intermediate in the top layer and very high in the basal bed. »Mollusc fragments» are very frequent below the unconformity. The distribution of sponge spicules and »mollusc fragments» contributes to confirm the suggested correlation of core 56 with core 57. An echinoid spine was found in the basal bed.

.11 Mineral grains and rock fragments. The concentration of allogenic mineral grains and rock fragments $> 150\,\mu$ is low and exceeds 20/g only in one case, viz. at 78 cm. The present top of the truncated sequence is strongly encrusted by manganese micronodules, indicating a considerable time of nondeposition.

.12 Diagenesis. The top layer above the unconformity is very loose as a contrast to the high strength of the manganese encrusted present top of the truncated beds. A second strength maximum is attained at 78 cm. The salinity distribution is of interest as there is a conspicuous maximum in the strongly indurated deposit below the unconformity. The high salinity of the dark, phosphatic clay member above the Tertiary calcareous clay is a feature which is also repeated in core 57. The diagenesis has proceeded very far in the dark clay member of core 56, especially between 80 and 40 cm, the deposit being hard and brittle and having a slaty texture.

.13 Stratigraphy. The high concentration of well preserved radiolaria, as well as the comparatively high carbon and nitrogen content of the sediment above the unconformity, indicates a young age of this deposit. The sequence in the truncated beds displays striking similarities to the sequence in core 57; a phosphatic clay member, P $(4 + 2\,x)$, with a high content of »mollusc fragments», with recurrent spongiae and radiolaria and with a high salinity in spite of the extensive induration, resting on a calcareous deposit which in the case of core 57 is indicated to be of Tertiary age. It is therefore believed that the contact between the calcareous — siliceous deposit and the overlying phosphatic clay member P $(4 + 2\,x)$ is approximately equivalent in these two cores. Only approximate equivalency can be assumed as this contact appears to reflect the progressive Cenozoic southward movement of the calcium carbonate compensation line and is thus younger the closer it is found to the present compensation line.

The extensive cementation with manganese of the member P $(4 + 2\,x)$ in core 56 probably indicates a very low rate of deposition and it is thus possible that this member corresponds to more than one meter or perhaps the entire top bed present in core 57.

At the coring the same accident happened as at the collection of core 55 and the piston corer in this case too, acted as an ordinary tube corer. The tube had penetrated approx. 3 m into the bottom. It is thus very probable that only the top layer of the loose beds above the unconformity was sampled and that most of the sediment from these beds was pushed aside. Due to the high strength and low plasticity of the member P $(4 + 2\,x)$ and lower, it does not seem likely that this part of the sequence was much distorted.

Core 57

East Eupelagic Area

(North Equatorial carbonate facies—North Equatorial silica facies)

Station no. 87.

Lat. 8° 25′ N. *Long.* 128° 48′ W.

Depth 4 607 m.

Length of core 485 cm.

Topography: Smoothly undulating bottom of the general type met with in this area was recorded approx. 9 km before the station. During this the ship drifted over a seamount approx. 180 m high. The long core was raised from near the highest point passed by the ship and the short core 57 B from the slope of the mount. A few hours later a series of three similar shield-formed elevations were passed. The highest one was approx. 150 m high and 10 km broad.

Abstract of interpretation. The core consists of Tertiary deposits uncovered by erosion of a shield-formed elevation. Further down the slope deposition prevails and the deposit is believed to consist of normal eupelagic

matter with admixture of locally eroded, suspended, sorted and redeposited sediments.

The Tertiary sequence consists of a series of siliceous clay beds with alternating high and low phosphorus content. These overlie conformously calcareous Tertiary beds consisting of foraminiferal marl and calcareous clay.

There are at least two explanations of the change from carbonate to clay facies recorded by the Tertiary sequence of this core, viz. through a general cooling of the deep water of the ocean and through a rearrangement of the surface current distribution. These possibilities as well as the regional stratigraphy are further discussed in part 3 together with evidence from other cores. As a reason for the change from depositional to erosional conditions might be assumed updoming caused by laccolithic intrusion of lava at a high level in the sedimentary sequence.[1])

.1 Calcium carbonate. Core 57 B which probably represents Late Pleistocene and Recent consists of clay free from carbonate, covered by 8 cm of calcareous clay.

The truncated core 57 consists of a carbonate-free phosphatic clay, overlying 10 cm of calcareous clay and a marl bed of unknown thickness.

.2 Titanium. The concentration of titanium is subject to variations from 350 to 650 · 10^{-5} in the clay bed probably due to the changes in accumulation of biogenous silica, to variations in the postdepositional precipitation of migrating manganese, and in two cases to occasional influx of abnormally great amounts of allogenic mineral grains and glass.

.3 Silica. Because of the uncontrolled rate of precipitation of manganese, the amount of biogenous silica could not be calculated from the titanium content.

.4 Organic matter. The carbon-nitrogen relationship is shown in fig 2.57.4, where the values from the calcareous bed and the clay

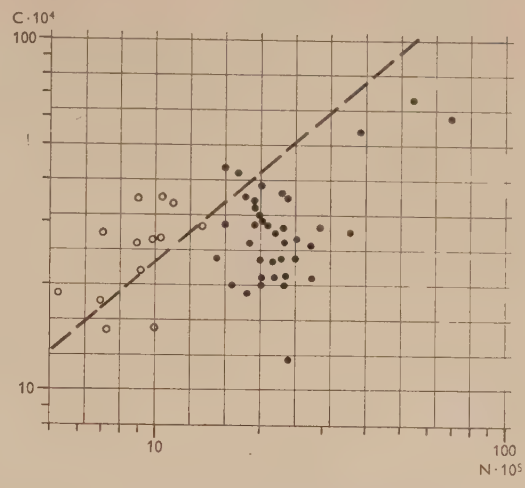

Fig. 2.57.4. Relation between carbon and nitrogen concentrations in core 57. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits. Open circles correspond to calcareous Tertiary samples, filled circles to Tertiary and Pleistocene siliceous clay samples.

have been separated. The former ones agree with the normal average for Pleistocene eupelagic marl and chalk oozes and the latter ones approach the distribution field typical for eupelagic clays. On the whole the distribution much resembles that found in core 53 (fig 2.53.4). It is interesting to note that the

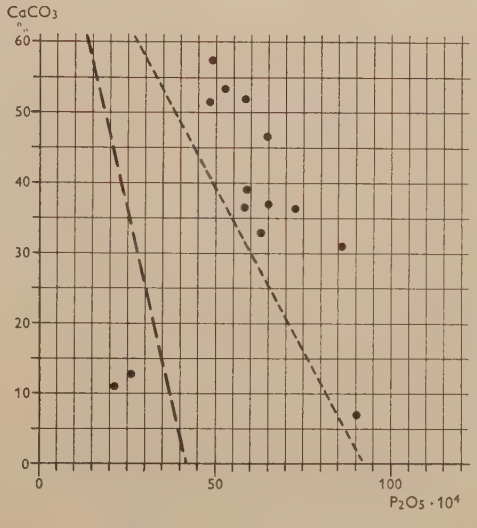

Fig. 2.57.5.1. Relation between calcium carbonate and phosphorus in calcareous samples from core 57 and 57 B. The heavy dashed line corresponds to the calcareous eupelagic average and the light line to the average of core 53 (calcareous Tertiary). The two samples in the left lower corner of the diagram correspond to the calcareous (Postglacial) samples of core 57 B.

[1]) On the basis of result recently obtained, Dr. R. Revelle has suggested a change of water depth in the Pacific as an additional possible explanation. This is valid also in the cases of cores 53 and 56.

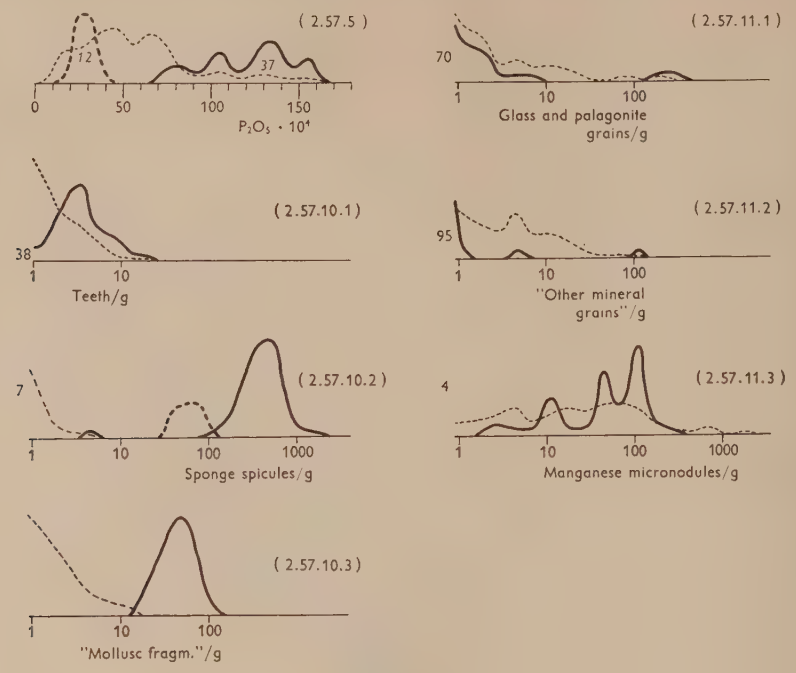

Fig. 2.57.5—10—11. Frequency distribution of phosphorus, »other fossils», rock fragments and mineral grains in core 57. Details with regard to the construction of the diagrams are given in the caption of fig. 2.48.5—10—11.

abraded surface layer displays an abruptly increased content of organic matter. This is possibly caused by benthonic animals living on or passing the non-depositional bottom surface.

.5 Phosphorus. Both the calcareous clay (fig. 2.57.5.1, lowest two values) and the carbonate-poor clay (fig. 2.57.5, thick dashed line) of core 57 B are abnormally low in phosphorus, which probably indicates abnormal conditions of deposition. The calcareous Tertiary member CT 2 in core 57 (pl. 2.57 col. $CaCO_3$ and fig 2.57.5.1) is abnormally rich in phosphorus and the relationship $CaCO_3$ —P_2O_5 resembles the one found in core 53 (likewise calcareous Tertiary) although the steepness of the regression line is still greater in core 57 CT 2. The overlying clay beds are stratified with regard to phosphorus (pl. 2.57 col P_2O_5 and fig. 2.57.5.). In the member P (4 + 2 x — 2) the highest values (> 1.5 % P_2O_5) are attained which have been found in the East Pacific material of the Expedition. The phosphate content is used as a basis for the stratigraphical subdivision of the clay beds in core 57.

.6 Colour and pattern. Core 57 B is greyish-yellow and contains reduction bodies. A sharply confined layer was found between 27.5 and 26 cm. The lower boundary of this is level and the upper slightly undulating. Close to the upper boundary the overlying sediment contained numerous manganese nodules of approx. 0.5 mm size. This structure is believed to be of secondary origin.

The calcareous basal beds of core 57 are yellowish-brown and the overlying clay is dark brown. Reduction bodies are fairly frequent and the typical eye-form is often well developed.

.7 Foraminifera. The calcium carbonate of the top layer of core 57 B appears to consist mainly of foraminiferal fragments. No entire tests were found in core 57 B nor in the clay beds of core 57. The calcareous Tertiary beds contain planktonic foraminifera in concentrations varying between 20 and 200/g and ben-

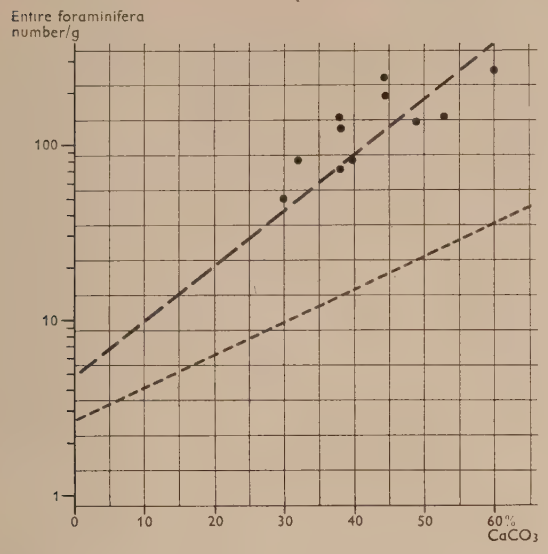

Fig. 2.57.7.1. Relation between concentration of entire foraminifera and calcium carbonate in core 57. The dashed line corresponds to the Pleistocene eupelagic average and the dotted line to the regression found in core 53 (calcareous Tertiary).

thonic foraminifera between 30 and 70/g. The member CT 2 in core 57 is therefore somewhat richer in benthonic specimens and much richer in planktonic ones than the calcareous Tertiary strata of core 53. The relationships between the content of carbonate, conc. foraminifera and conc. foraminiferal fragments display interesting similarities and differences in core 53 and 57. Thus the fragmentation (fig 2.57.7.2) appears to follow the same laws in both cores, the integrity index being high as compared with Pleistocene deposits of the corresponding foraminiferal concentrations and the number of fragments approx. three times the number of entire tests. With regard to the relationship calcium carbonate — conc. entire foraminifera (fig. 2.57.7.1) core 57 CT 2, however, differs markedly from core 53, the distribution in the former bed being practically identical with the one prevailing in eupelagic Pleistocene deposits. The relationships referred to reflect the depositional and postdepositional transformation of the foraminiferal test and the concentration of coccoliths, and are believed to be influenced mainly by the temperature of the bottom water and the intensity of mud eater activity (postdepositional carbon dioxide production in the sediment). The depositional environment of the two sediment types is thus judged to be similar but the differences which occur place the bed CT in core 57 closer to Pleistocene marl ooze conditions. It is therefore believed that the calcareous Tertiary beds of core 57 are younger than the calcareous Tertiary beds making up core 53.

The planktonic fauna is mostly dominated entirely by the genus *Globigerina*.

F. Brotzen who made a preliminary scrutiny of the benthonic fauna, states that this is of Tertiary age and makes the following comment:

»A very large specimen of *Vulvulina sp.* was found in the marl ooze bed. Until more individuals have been found it is difficult to determine the species. It is however very nearly related to such broad and thick speci-

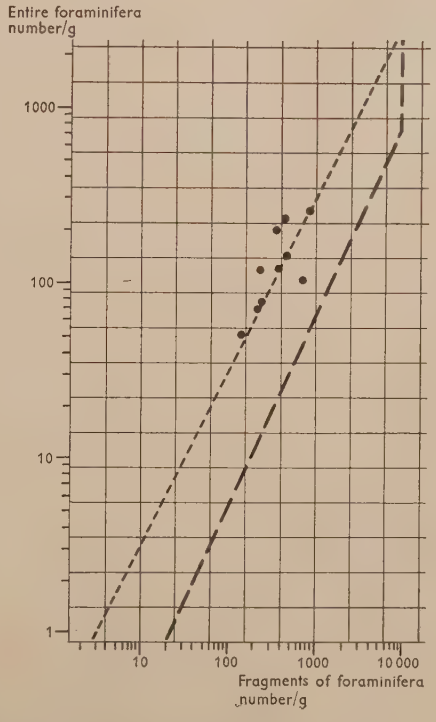

Fig. 2.57.7.2. Relation between concentration of entire foraminiferal tests and fragments of tests in core 57. The dashed line corresponds to the Pleistocene eupelagic average and the dotted line to the average of core 53.

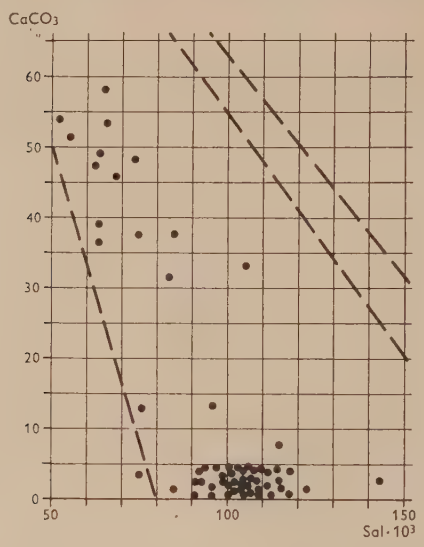

Fig. 2.57.12. Relation between calcium carbonate content and salinity in core 57. The dashed lines correspond to lines A, B and C in fig. 1.12.2.1 and 1.12.2.2.

mens which are hitherto described from the Lower and Middle Tertiary of the Caribbean region (Puerto Rico). Also some *Pleurostomella* species which are frequent in the marl ooze are more related to known Tertiary forms than to Recent ones.» —

It is hoped that a detailed investigation, undertaken by Dr. Brotzen, will give definite information with regard to the stage.

.*8 Radiolaria.* On the whole, core 57 is comparatively rich in radiolaria. The minimum at the present top of core 57 appears to be a secondary feature to judge from the extensive corrosion. A decreased rate of deposition of radiolaria is believed to be at least partly responsible for the decreased concentration in the intermediate clay bed but the traces of corrosion indicate that secondary dissolution is also involved. According to preliminary investigations undertaken by Mr. W. Riedel and Mr. A. Elger the fauna of the upper part of the clay bed as well as that of the marl ooze are of Tertiary age. Recent forms prevail in core 57 B. A closer description of the radiolarian faunas will appear elsewhere.

.*10 Other fossils.* The general concentration of fish teeth (fig. 2.57.10.1) is higher than in any of the other East Pacific cores. The greatest number is found in the top layer of core 57 B. Spongiae and »mollusc fragments» are also more abundant than in any of the other East Pacific cores. The exceptionally high concentration of noncalcareous fossils in the intermediate and upper parts of core 57 is believed to be a facies effect and to depend on the location of the core below the Equatorial Counter Current, which appears to have existed at least during the time corresponding to these clay beds.

.*11 Mineral grains and rock fragments.* Mostly the sediment contains only a few allogenic grains $> 150\ \mu/g$ but in two strata, viz. 300—290 cm and around 30 cm the concentration is suddenly increased to several hundred grains of pumice, glass, palagonite and »other mineral grains»/*g*. This material was most probably wind-borne as pumice cannot be expected to be formed in connection with submarine eruptions in water of greater depths than appr. 2 000 m (Rittmann, 1936, p 51, Mellis 1949, p. 200). — High concentrations of manganese micronodules occur in the marl bed and are frequent in the intermediate and lower part of the siliceous clay bed.

.*12 Diagenesis.* Owing to the fact that the sequence is truncated, the strength attains high values even at the present surface of core 57. Core 57 B on the other hand is loose [estimated strength = 10, (100 log H = 100)]. The maximum strength is attained in the clay member P ($4 + 2\,x - 1$) at 280 cm. As in the petrologically similar beds of cores 48 and 56 the salinity is very high in the siliceous clay of core 57. This is probably due to a high concentration of silica gel derived from the great amount of siliceous fossils. — The salinity is fairly well correlated to the carbonate content of the marl bed (fig. 2.57.12) and the relationship between the two variables is similar to that found in core 53 (fig 2.53.12).

.13 Stratigraphy. Both the lithology and the faunal composition indicate that the present top of core 57 is confined by an abrasion surface, that more than ten meters of the normal sequence have been eroded, and that Tertiary outcrops. In order to corroborate this conclusion a sample from 10 cm depth in core 57 was subjected to radium analysis.[1]) No measurable content of radium was found which confirms that the deposit is of great age.

The reasons for the change from a calcareous deposit to a siliceous clay are to be sought either in an increased rate of dissolution, or in a decreased rate of production of carbonate, or in both. The first alternative would mean that as early as in Tertiary time the growth of polar ice and the cooling of the deep and bottom water had proceeded far enough to allow the rate of dissolution of carbonates to equal and surpass the rate of production in this area. The second alternative implies that the facies change was due to a rearrangement of the production pattern of the Equatorial Pacific, i. e. to a change in the circulation pattern of the surface currents. These possibilities are further discussed in chapter 1.1, and in part 3. (See also footnote, § 2.57.0).

The location of core 57 close to the present calcium carbonate compensation line makes it probable that the calcareous Tertiary (CT) of this core represents the youngest calcareous deposits outside the present facies boundary. According to the nomenclature suggested (chapter 3.3) this member should therefore be designated CT 2. In order to avoid later confusion the definite numbering is however retained until this stratigraphically important area has been more closely sampled.

For the overlying clay beds a subdivision is suggested, which is based on the marked stratification with regard to phosphorus content. It is not known how many phosphorus maxima and minima occur in the hiatus between the top of core 57 and the member P 4, represented in conformous clay sequences (e. g. core 51 and 54). Until this is revealed by future investigations of suitable cores from the East Eupelagic Area, the lowest P-member of core 57 is labelled P $(4 + 2\,x)$, the overlying member, with a decreased phosphate content P $(4 + 2\,x - 1)$ a. s. o., $2\,x$ being the total and hitherto unknown number of pairs of maxima and minima occurring between P 4 and the level equivalent to the CT-contact in core 57.

Core 58

East Eupelagic Area

(North Equatorial carbonate facies)

Station no. 88.

Lat. 6° 44′ N, *Long.* 129° 28′ W.

Depth 4 440 m.

Length of core 991 cm.

Topography: Before the station the bottom was sloping upwards approx. 100 m for 10 km (fig 2.58.0).

Abstract of interpretation. The station is situated fairly close to the calcium carbonate compensation boundary and the rate of carbonate accumulation is therefore low as compared with this rate in other calcareous cores. The lower part of the column appears to have been deposited in connection with comparatively low rates of production and dissolution of calcium carbonate. This part of the sequence is assumed to be of Pliocene age. The climatological boundary Pliocene — Pleistocene has been drawn at 395 cm (extra-

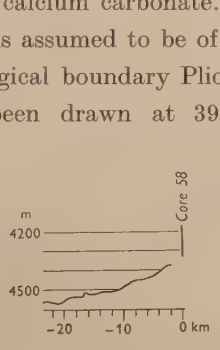

Fig. 2.58.0. Bottom topography in the vicinity of the station of core 58. Redrawn from Koczy (contribution to vol. IV).

[1]) This analysis was carried out by Dr V. Kröll at the Oceanographic Institute of Gothenburg. The author is indebted to Prof H. Pettersson for making the radium investigation possible.

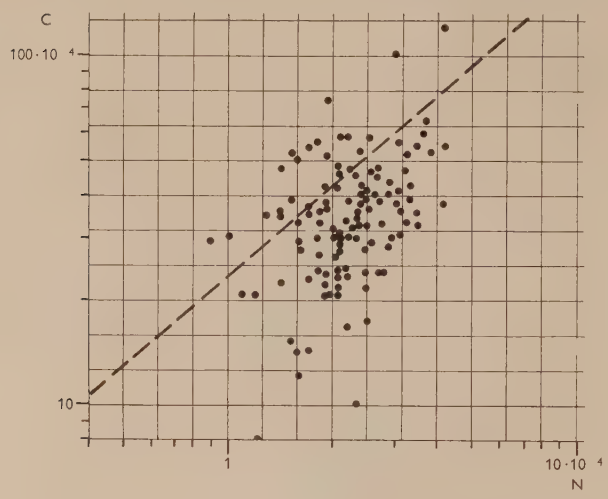

Fig. 2.58.4. Relation between carbon and nitrogen concentrations in core 58. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits.

polated age slightly less than 1 000 · 10^3 years) where the rate of accumulation of carbonate increases strongly in spite of the apparently increased rate of dissolution. The Pleistocene part of the sequence contains nine maxima and nine minima of rate of calcium carbonate accumulation, Recent being connected to the last minimum (core 58 A). The estimated age of the last maximum is 52 000 years and of the last but one minimum approx. 185 000 years.

Due to the thinness of the correlated Pleistocene stages, the age determinations by titanium content are markedly influenced by the experimental errors. The agreement between the calculated ages of the lowest correlated stage in core 60 and 58 is, however, regarded as fairly good (5 %). The average discrepancy between the corresponding titanium ages calculated in core 60 and 58 amounts to 103 % of the time included in the central stratum of the correlated stage. This is regarded as satisfactory especially as the sign of the anomalies is reversed several times.

.1 Calcium carbonate. The normal eupelagic carbonate stratification is well developed and the changes in the carbonate content are very marked. The Pleistocene part of the sequence consists of marl ooze with several chalk ooze strata and with strata of marly clay. The Pliocene part is dominated by marl ooze intercalated with clay and a few chalk ooze layers. On account of the low average rate of calcium carbonate accumulation the Pleistocene series are only four meters thick.

.2 Titanium. The distribution of titanium is very regular and no marked changes in the rate of minerogenous accumulation are indicated. The constancy from stage 15 to Recent is checked by lateral control. Under the assumption of constancy from the lowest stage represented, the basal level has an age of 253 · 10^4 years.

.3 Silica. The calculated amount of biogenous silica exceeds 30 % only in one thin stratum around 765 cm. The average content of biogenous silica is considerably higher in the

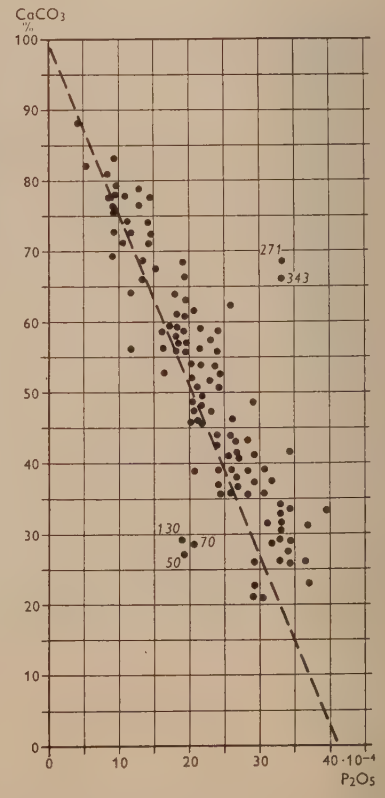

Fig. 2.58.5. Relation between concentration of phosphorus and concentration of calcium carbonate in core 58. The dashed line corresponds to the estimated eupelagic average.

Pliocene (approx. 18 %) than in the Pleistocene (approx. 12 %) part of the sequence.

.4 Organic matter. There is almost no correlation between carbon and nitrogen (fig 2.58.4) and the variations in nitrogen concentration are much smaller than in carbon concentration. A conspicuous carbon maximum is found in the upper marl ooze of stage 9. The accumulation of carbon per unit time is remarkably high in the basal Pliocene chalk ooze (230 cfor)[1]) as well as in a few Pleistocene strata but is as an average low (95 cfor) in comparison with the cores 59 and 60 (both 370 cfor). These averages are calculated from stage 15 to Recent.

The corresponding values for nitrogen are 5.2 cfor in core 58, 11.7 in core 59, and 15.0 in core 60.

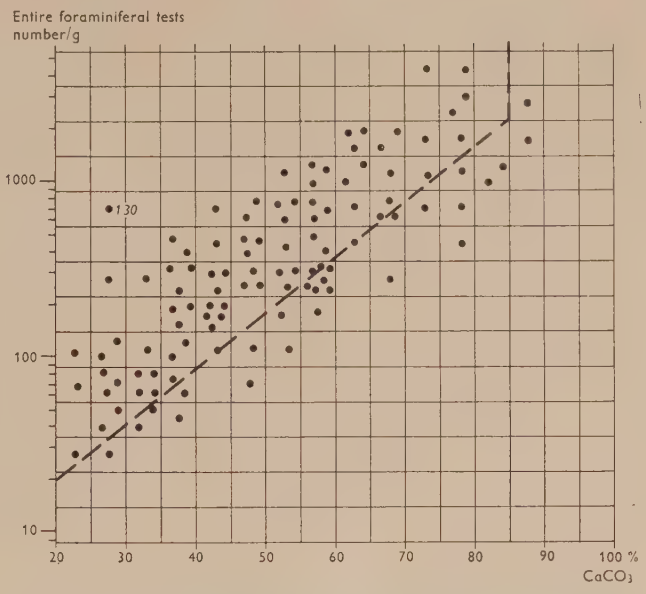

Fig. 2.58.7.1. Relation between concentration of entire foraminiferal tests and percentage of calcium carbonate. The dashed line illustrates the average eupelagic conditions.

Sample 130 belongs to stage 7 and is abnormally rich in foraminifera. The reason for this is not known.

.5 Phosphorus. As a general rule the phosphorus concentration is high due to the high average content of clay. In the lower part of fig 2.58.5. the values are distributed to the right of the guide line, owing to the comparatively low amount of biogenous silica in this core. In a few cases the phosphorus contents are abnormally low (50, 70, 130); these samples form a separate group in the diagram. Two samples occur, which are abnormally rich in phosphorus (271, 343). This is believed to be due to post-depositional migration.

The average rate of accumulation of phosphorus is low (40 cfor since stage 14) in comparison with e. g. core 60 (58 cfor).

.6 Colour and pattern. The hue is very constant but blackness and shade vary considerably and frequently, especially in the strata above 735 cm. The blackness appears to be dependent of the concentrations of carbonate, organic matter and finely dispersed manganese and ferric compounds. The Pliocene marl ooze bed 935—868 cm is remarkably light coloured. Especially the Pliocene beds are very rich in beautifully developed mud-eater traces of all kinds (pl. 2.6.3, 2.6.4, and 2.6.9).

.7 Foraminifera. The concentration of planktonic foraminifera varies greatly from a few specimens to several thousand per gram sediment and the total concentration of entire foraminiferal tests is well correlated with the calcium carbonate concentration (fig 2.58.7.1). As is seen from this graph the number of foraminifera per unit weight of calcium carbonate is higher in core 58 than the average for the East Eupelagic Area. These conditions are also found in core 59. The reasons are not known.

The concentration of planktonic foraminifera is well correlated with the concentration of benthonic foraminifera (fig 2.58.7.2) and the regression is less steep than the East Eupelagic average. This is believed to be due to the great differences in postdepositional dissolution between some of the Pliocene strata (left, lower part of distribution) and some of the Pleistocene high circulation strata (right, upper part of the distribution). The

[1]) 100 cfor = 1 for = 1 mg/cm² · 1000 years.

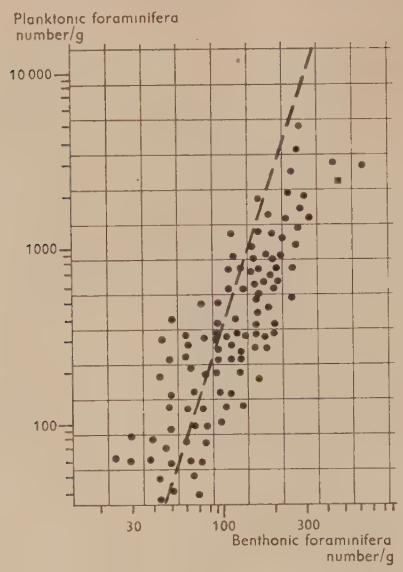

Fig. 2.58.7.2. Relation between concentration of entire tests of planktonic and benthonic foraminifera in core 58. The dashed line corresponds to the estimated eupelagic regression (§ 1.7.2).

The comparatively low enrichment of benthonic tests in low foraminiferal concentrations is believed to be an effect of the comparatively low rate of dissolution in the Tertiary strata. The abnormally high concentrations of benthos corresponding to high concentrations of planktonic tests occur in the strata which are interpreted as glacial and are believed to reflect the marked increase of the rate of biogenous deposition, which is not followed by a correspondingly increased rate of accumulation of planktonic tests because of the high rate of dissolution in these ages and the vicinity to the carbonate compensation line.

Pleistocene average accumulation of benthos (since stage 15) is low (34 individuals/cm² · 1 000 years) as compared with core 59 (167 ind.) and core 60 (134 ind.).

The planktonic fauna is dominated by *Globorotalia* in the marl ooze and the clay and in a few cases also in the chalk ooze. The general relationship in this facies between concentration of planktonic foraminifera and percentage of *Globorotalia* is found also in core 58 (fig 2.58.7.3). The chalk ooze is mostly dominated by *Globigerina* and in the Pleistocene beds also by *Pulleniatina obliquiloculata*. The marked decrease in the Pleistocene beds of the group *Sphaeroidina* + *Sphaeroidinella* is due to reduction of the percentage of *Sphaeroidinella dehiscens*.

.8 Radiolaria. The accumulation of radiolaria is considerably lower than in the south neighbouring cores. The average amounts to approx. 450 individuals/cm² in 1 000 years in the lower part of the Pliocene sequence represented and rises to approx. 1 000 ind/cm² · 1 000 years in the upper Pliocene and Pleistocene beds. Corrosion is frequent.

.9 Diatoms. Particularly in the clay strata the frustules are strongly corroded and the original size distribution of *Coscinodiscus nodulifer* might be affected. The 40 μ-frequency maximum prevails from the bottom to the top of the core. The upper 1 % — curve is usually lower than 100 μ and does not pass above 140 μ except in the layer 120—60 cm where it rises to 160 μ. This rise is supposed to be a trace of the normal frequency maximum in big sizes extending from stage 6 to stage 3.

.10 Other fossils. Single specimens of fish teeth occur at several levels. A fish vertebra was found at 370 cm.

.11 Mineral grains and rock fragments. Small fragments of pumice and compact glass occur sporadically and are presumably windborn. Manganese micronodules occur but do not exceed 50/g.

.12 Diagenesis. The strength of the upper 3 m and of the basal beds is regarded as low and of the beds 300—830 as normal in comparison with core 51. The salinity is low in view of the carbonate content and is well correlated with this (fig 2.58.12). Recrystallization of foraminifera is far-reaching in the Pleistocene beds and still more in the Pliocene ones. Traces of corrosion of the tests are frequent. Recrystallized tests appear to be more resistant to corrosion than the original structures.

.13 Stratigraphy. Due to the location of the core close to the North Equatorial carbonate facies boundary the rate of accumulation of biogenous matter and therefore also the total rate is low. As a consequence this 990 cm core penetrates further back in time than any

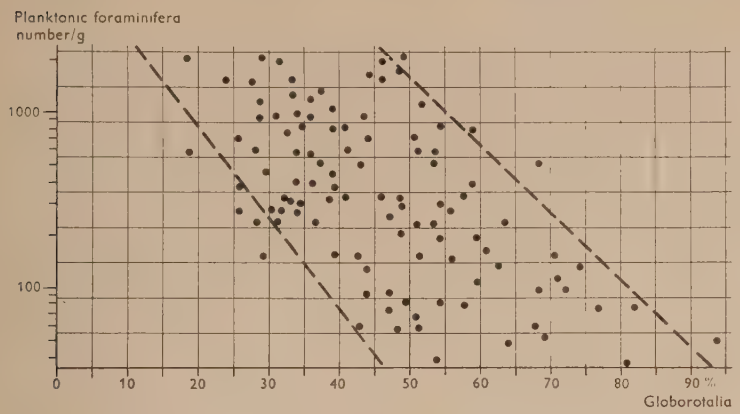

Fig. 2.58.7.3. Relation between concentration of entire tests of planktonic foraminifera and planktonic faunal percentage of *Globorotalia menardii + tumida*. The guide lines coincide roughly with the eupelagic equiprobability curve 0.05, i. e. the probability of occurrence of a eupelagic sample outside these boundaries is less than 10 percent.

of the other equifacial cores. As was mentioned above (§ 2.58.2) the basal layer is likely to have an age of 2.5 million years and the one million year limit (Σ TiO_2 = 535 mg/cm²) appears to be located at 396 cm, close to the Pliocene-Pleistocene boundary, as defined below.

Even in the Pliocene part of the sequence very marked changes occur in the rate of accumulation of calcium carbonate. This rate is, however, believed to have a much smaller production component than in the Pleistocene beds, as the dissolution component appears to have been comparatively small in Pre-Pleistocene time. The stratigraphical units below stage 18 have not been labelled, as the facies conditions make it difficult to distinguish between stages and substages and as there is no other core investigated which penetrates into explicitly correlatable strata.

It does not appear possible to define palaeontologically the Pliocene-Pleistocene boundary in pelagic sediments except as a thick transition zone. The marked climatological change from Pliocene to Pleistocene conditions is however believed to be recorded in core 58 at appr. 395 cm. This level, with Σ TiO_2 = 527 mg/cm² and the approximate age 10^6 years (10^6 years = 535 mg TiO_2/cm²), is suggested as a climatological Pliocene — Pleistocene boundary in pelagic deposits.

The significance of the relative amplitudes of the variations in calcium carbonate concentration are discussed in chapter 1.1.

Table 2.58.13 contains a comparison between the total amount of TiO_2 in a 1 cm² column, extending from the surface to assumedly equivalent stages in core 60 and 58. Column 1 gives the stage or substage numbers, col. 2 the estimated borders of the central stratum of the stage, and col. 3 the location of its center in core 60. The amount of TiO_2 (d_0) in the central stratum is an expression for the limits of stratigraphical uncertainty inherent in the correlation. This amount, as estimated in core 60, is shown in col 6, expressed in mg TiO_2/cm² (5.3 mg TiO_2/cm² = 10^4 years). Col. 4,5, and 8 give the amount of TiO_2 deposited per cm² since the times corresponding to the depths indicated in col 2,3, and 7. As the tops of the columns

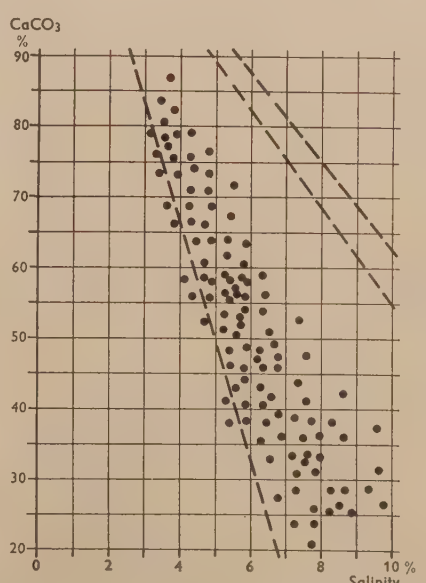

Fig. 2.58.12. Relation between calcium carbonate content and salinity in core 58. The dashed lines correspond to lines A, B and C in fig. 1.12.2.1 and 1.12.2.2.

TABLE 2.58.13

1	2	3	4	5	6	7	8	9	10	11
	Core 60					Core 58				
Stage or Substage no.	Depth, cm		Σ TiO_2 mg/cm²		TiO_2-content of central stratum, mg/cm² = d_0	Depth, cm	Σ TiO_2 mg/cm²	Σ TiO_2 (core 60) — — Σ TiO_2 (core 58) = d	Stepwise change in d mg TiO_2/cm² = Δd	$\frac{\Delta d}{d_0}$
	Borders of central stratum	Center of central stratum	Borders of central stratum	Center of central stratum		Center of central stratum				
2	50 170	120	14 30	24	16	3	35	—11	—11	0.69
3	210 260	230	48 75	61	27	50	98	—37	—26	0.96
4	290 350	320	85 108	95	23	60	102	— 7	+30	1.30
5	400 412	408	135 144	141	9	70	130	+ 11	+18	2.00
6	479 495	487	175 180	177	5	90	160	+17	+ 6	1.20
7	507 520	517	185 196	195	11	130	221	—26	—43	3.90
8	560 620	600	220 248	239	28	150	236	+ 3	+29	1.04
9	666 674	669	275 284	282	9	174	282	0	— 3	0.33
10	680 760	725	285 306	296	21	190	299	— 3	— 3	0.14
11	775 795	790	313 326	324	13	215	336	—12	— 9	0.69
12	800 860	830	327 342	335	15	228	357	—22	—10	0.45
13	880 900	890	351 357	354	6	250	399	—44	—22	3.66
14	950 1 000	985	372 382	378	10	270	407	—29	+15	1.50
										m = 1.37

have been truncated at the coring, a correction has been made for the amount of titanium deposited since the formation of the present top of the core. In the case of core 58 this correction is estimated from the correlation with the short core 58 B, which contains the undisturbed surface layer. This correlation indicates that the surface layer missing in core 58 probably corresponds to the entire core 58 B (37 cm) and to the value Σ TiO_2 = + 27mg/cm². The corresponding correction in core 60 is carried out by correlation with core 61 B and the top of core 61. The top of core 60 is thus estimated to be equivalent with a level situated between 17 and 21 cm in 61 B and the corresponding value of Σ TiO_2 = + 4. The corrected amounts of TiO_2 are entered in the table.

If the composition of the lutite and the rate of minerogenous accumulation were permanently identical at the localities 58 and 60, if the samples investigated were fully representative of the intervening parts of the sequence, and if there were no analytical

errors, the values of col 5 and col 8 would agree within the limits of stratigraphical uncertainty (d_0). The difference, (d), between corresponding values in col. 5 and 8 (col. 9) should thus be equal to or smaller than d_0 (col. 6). If any error enters one of the values d (col. 9) it will also influence the subsequent values. In order to follow the discrepancies entering in each stage, the stepwise change downwards in d has been calculated (Δ d in col. 10). The ratio between Δ d and the allowed change d_0 is indicated in col. 11. In normal cases Δ d/d_0 should not greatly exceed 1.

The fact that Δ d reverses its sign several times indicates that there is no systematical error involved, e. g. a permanent difference in the rate of minerogenous accumulation in core 58 and 60. The greatest anomalies are found in the stages 5, 7 and 13. The sources of error which are believed to have the greatest relative influence in the case of core 58 are the thinness of the Pleistocene series and the high titanium concentrations. Both these factors cause a comparatively great error in Σ TiO_2 if the samples analyzed are not fully representative of the intervening parts of the column. The significance of the deviations are further treated in § 1.2.5.

The probable age of the center of stage 14 corresponds to Σ $TiO_2 = 378$ ($713 \cdot 10^3$ years) as calculated in core 60 and 407 in core 58. The difference (29) minus the amount of TiO_2 in the central stratum (10) amounts to 19 mg TiO_2/cm^2 corresponding to $36 \cdot 10^3$ years or 5 % of the assumed age. This result is regarded as a satisfactory indication of agreement in the rate of minerogenous accumulation in the present cases.

The average deviation of corresponding titanium age values in cores 58 and 60 amounts to Δ $d/d_0 = 1.37$. A comparison of the average deviations found in different cores is given in § 1.2.5.

Core 59

East Eupelagic Area

(North Equatorial carbonate facies)

Station no. 90.

Lat. 3° 05′ N, *Long.* 133° 06′ W.

Depth 4370 m.

Length of core 972 cm.

Topography: Slightly undulating bottom.

Abstract of interpretation. The station is located below the South Equatorial Current. The rate of carbonate accumulation varies with time in the normal way, the maximum rate is high, viz. 2.4 kfor (highest value recorded in the Pacific = 8.2 kfor in core 62) and the minimum = 0.11 kfor. As a result both stages and substages are well developed. The changes with time of the size distribution of *Coscinodiscus nodulifer* are marked and give additional aid to the correlation. The only ambiguity involved is caused by the comparatively high rate of carbonate accumulation in the substage 8.4. The lowest correlated substage is 14.2 with a titanium age of $691 \cdot 10^3$ years. The average error of twenty age determinations is only 90 % of the stratigraphical uncertainty.

As usual the top of the column was truncated at coring. The material lost is, by correlation with core 61 B, estimated to contain 4.8 mg TiO_2/cm^2 corresponding to $9 \cdot 10^3$ years. Core 59 B was lost due to the low cohesion of the surface deposit.

.1 *Calcium carbonate.* The normal eupelagic carbonate stratification is well developed and the changes both in carbonate content and in rate of accumulation of carbonate are very marked although not as strong as in the

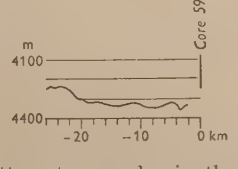

Fig. 2.59.0. Bottom topography in the vicinity of the station of core 59. Redrawn from Koczy (contribution to vol IV).

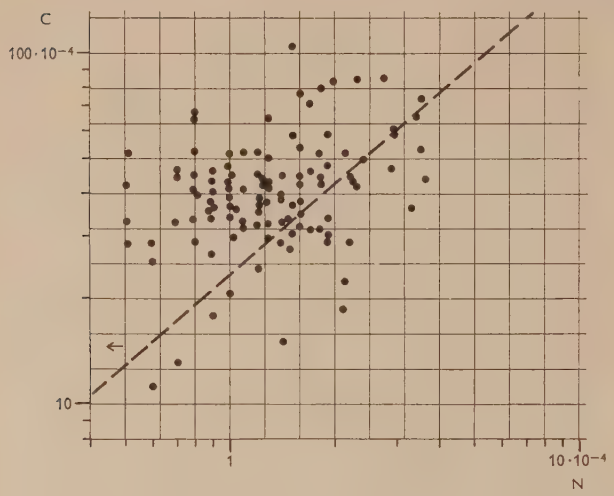

Fig. 2.59.4. Relation between carbon and nitrogen concentrations in core 59. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits.

neighbouring core 60. The sequence is dominated by globigerina and globorotalia chalk ooze intercalated with globigerina and globorotalia marl ooze and with a thin layer of radiolarian ooze. The rate of carbonate accumulation is high in comparison with core 58 and varies between 0.1 and 2.4 kfor $CaCO_3$.

.2 Titanium. The distribution of titanium is regular and no marked changes in the rate of minerogenous accumulation are indicated (s. f. § 2.59.13).

.3 Silica. The percentage of biogenous silica increases in the carbonate minima less than is required by the lowered dilution with calcium carbonate and the increased concentration of biogenous silica is thus corresponded by a decreased rate of accumulation (appr. 25—30 % of the maximum value.) Only in one case is petrographical dominance attained, viz. in stage 5.

.4 Organic matter. Both the carbon and nitrogen concentrations tend to be decreased in the carbonate accumulation maxima. This decrease, however, appears to be caused by the dilution with calcium carbonate as the calculated rates of accumulation of C and N increase. This latter effect is believed to be due partly to an increased rate of production and deposition, partly to a lowered rate of decomposition in the rapidly deposited strata. The average rate of accumulation of carbon since age 15 is the same as in core 60, viz. 370 cfor and of nitrogen somewhat less (12 cfor) in core 59 than in 60 (15 cfor). The samples scatter widely in the C—N diagram (fig. 2.59.4).

.5 Phosphorus. Considerable amounts of biogenous silica in the carbonate-poor strata tend to displace the relationship $CaCO_3$—P_2O_5 to the left of the guide line of fig. 2.59.5. One sample (443) is abnormally rich in phosphorus. — The average rate of accumulation of phosphorus since stage 14 is higher (71 cfor) than in core 60 (58 cfor).

.6 Colour and pattern. The hue of the deposit is very constant and the marked

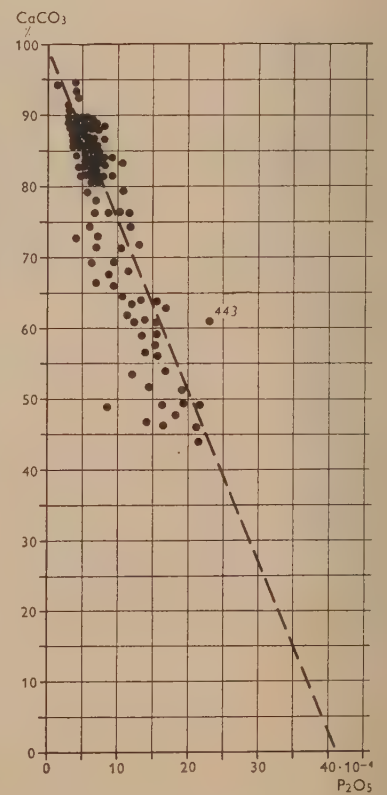

Fig. 2.59.5. Relation between concentration of phosphorus and concentration of calcium carbonate in core 59. The dashed line corresponds to the estimated eupelagic average.

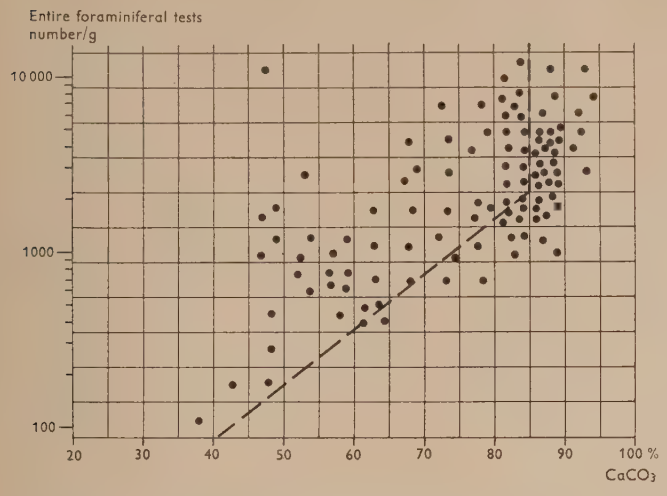

Fig. 2.59.7.1. Relation between concentration of entire foraminiferal tests and percentage of calcium carbonate. The dashed line illustrates the average eupelagic conditions.

The single sample abnormally rich in entire tests is no. 150, belonging to stage 3. The reason for the deviation might be residual enrichment by dissolution of coccoliths (cf. fig. 2.60.7.1).

changes in blackness appear mainly to be related to the changes in carbonate content. Traces of bottom scavengers are very frequent (pl. 2.6.4) and an unusually good longitudinal section of a worm channel was obtained between 473 and 466 cm (pl. 2.6.9).

.7 *Foraminifera.* The concentration of planktonic foraminifera varies from 150 to 12 000 entire specimens per gram sediment and the number of entire tests is fairly well correlated with the calcium carbonate concentration (fig. 2.59.7.1). Most of the deviations appear where the decreased carbonate content is not followed by the normal corresponding decrease in total rate of accumulation, i. e. where the content of biogenous silica is high. In such cases the comparatively high rate of accumulation prevents the far-reaching fragmentation which is normally connected to low contents of carbonate in Pleistocene deposits.

The linear correlation log conc. planktonic foraminifera/log conc. benthonic foraminifera (fig. 2.59.7.2) is not as good as in core 58 and the regression line might be curved. The average rate of accumulation of benthonic foraminifera since age 15 is higher (167 specimens/cm² · 1 000 years) than in the neighbouring core 60 (134/cm² · 1 000 years).

Of the planktonic genera only *Globigerina* and *Globorotalia* attain dominance, *Globorotalia*-dominance mostly being restricted to the carbonate minima, or to the strata close to these. In the deepest parts of the carbonate accumulation minima the *Globorotalia*-dominance appears to be markedly counteracted by selective dissolution. Substage 8.4, which is remarkable also from other points of view (cf § 2.59.13), is almost entirely dominated by *Globorotalia* in spite of the high carbonate content. With the exception of this anomaly and the two siliceous strata, where the *Globorotalia* percentages are, for reasons quoted above, abnormally low, the correlation conc. plank-

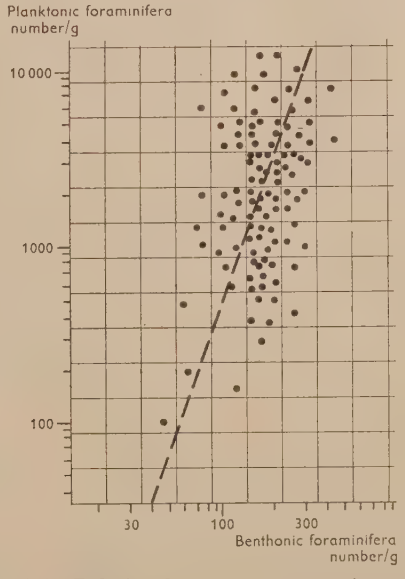

Fig. 2.59.7.2. Relation between concentration of entire tests of planktonic and benthonic foraminifera in core 59. The dashed line corresponds to the estimated eupelagic regression (§ 1.7.2).

The concentration of benthos is poorly correlated with the concentration of planktonic tests when this latter concentration is high. This is believed to indicate that the concentration of benthos is to a great extent determined by secondary enrichment. The modifying influence of ecological factors is traceable in the distribution of samples low in foraminifera.

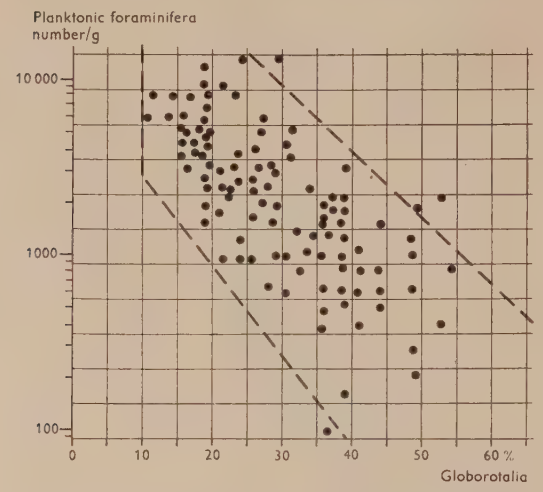

Fig. 2.59.7.3. Relation between concentration of entire tests of planktonic foraminifera and planktonic faunal percentage of *Globorotalia menardii* + *tumida*. The guide lines coincide roughly with the eupelagic equiprobability curve 0.05, i. e. the probability of occurrence of a eupelagic sample outside these boundaries is less than 10 percent.

tonic foraminifera/percentage of *Globorotalia* is good (fig. 2.59.7.3).

.8 *Radiolaria.* The concentration of radiolaria $> 150\ \mu$ is intermediate to high and varies between 1 000 and 50 000 specimens per gram sediment. The peaks in the concentration occur largely in the carbonate minima, but the calculated rates of accumulation (pl. 2.59, col. Radiolaria) demonstrate that the peak values are largely to be ascribed to the decreased dilution with calcium carbonate. The maximum average rate of accumulation appears to have taken place in the age group 6—3.

.9 *Diatoms.* The diatoms are in a good state of preservation and the changes in the size distribution of *Coscinodiscus nodulifer* are very marked. By far the most pronounced frequency maximum in big sizes is as usual found in stage 4 and the development of this maximum starts already in stage 5. Smaller maxima or increased frequencies of big sized frustules are found in the stages 2, 6, and 8. Below this stage no very marked changes occur, except possibly in stage 11 where the 30—40 μ size-frequency rises above 30 %.

.11 *Mineral grains and rock fragments.* A grain of pumice was found at 443 cm in a sample corresponding to 0.9 g sediment. Manganese nodules occur in many levels but only in small amounts.

.12 *Diagenesis.* The radiolaria are very well preserved and the foraminifera do not appear to be markedly corroded in the carbonate maxima. Recrystallization of foraminifera is frequent. The average increase of strength with depth is very much the same as in core 51 and the variation of strength with carbonate content is superimposed on this logarithmically linear function. The correlation between calcium carbonate and salinity is good (fig. 2.59.12).

.13 *Stratigraphy.* The lowest stage represented is lower 14 or upper part of 15. As is normal, especially in calcareous deposits, the top was truncated by the corer and the missing stratum is correlated with 21—0 cm in core 61 B, corresponding to $\Sigma\ TiO_2 = 4.8$ mg/cm². When comparing core 58 with core 60 (§ 2.58.13) it was not possible to correlate smaller time-rock units than stages, due to the low rate of accumulation in the former case. Both core 59 and 60, however, give such a detailed stratigraphical record that it is in

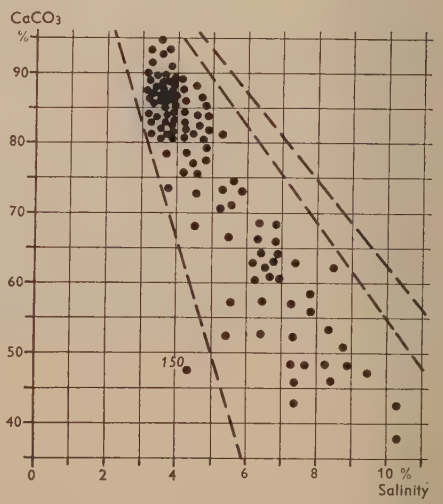

Fig. 2.59.12. Relation between calcium carbonate content and salinity in core 59. The dashed lines correspond to lines A, B and C in fig. 1.12.2.1 and 1.12.2.2.

TABLE 2.59.13

1	2	3	4	5	6	7	8	9	10	11
	Core 60					Core 59				
Stage or Substage no.	Depth, cm		Σ TiO_2 mg/cm²		TiO_2-content of central stratum, mg/cm² = d_0	Depth, cm	Σ TiO_2 mg/cm²	Σ TiO_2 (core 60) — — Σ TiO_2 (core 59) = d	Stepwise change in d mg TiO_2/cm² = Δd	$\frac{\Delta d}{d_0}$
	Borders of central stratum	Center of central stratum	Borders of central stratum	Center of central stratum		Center of central stratum				
2.2	109 181	150	23 32	27	9	90	39	—12	—12	1.33
3.1	205 225	215	44 58	52	14	160	61	— 9	+ 3	0.21
3.2	225 249	235	58 66	64	8	175	68	— 4	+ 5	0.63
3.3	249 264	257	66 77	75	11	210	92	—17	—13	1.18
C 4	260 288	275	76 85	80	9	215	94	—14	+ 3	0.33
4.2	288 308	298	85 91	88	6	242	102	—14	0	0.00
4.4	338 365	361	103 114	112	11	299	124	—12	+ 2	0.22
5	400 412	408	135 144	141	9	325	139	+ 2	+14	1.56
6	479 495	487	175 180	177	5	376	160	+17	+15	3.00
7	507 520	517	185 196	195	11	410	177	+18	+ 1	0.09
8.2	520 545	527	196 210	199	14	424	185	+14	— 4	0.29
8.4	562 618	588	220 247	233	27	470	204	+29	+15	0.56
8.6	644 665	651	260 269	264	9	563	248	+16	—13	1.44
9	666 674	669	275 284	282	9	635	271	+11	— 5	0.56
10	680 760	725	285 306	296	21	687	295	+ 1	—10	0.47
11	775 795	790	313 326	324	13	739	315	+ 9	+ 8	0.62
12.2	810 830	820	330 335	332	5	791	333	— 1	—10	2.00
12.4	847 865	859	338 346	342	8	850	347	— 5	— 4	0.50
13	880 900	890	351 357	354	6	895	361	— 7	— 2	0.33
14.2	960 995	975	374 380	376	6	920	366	+10	+17	2.83
										m = 0.90

many cases possible to identify and correlate also substages. At the final adjustment of the correlation, the curve of rate of calcium carbonate accumulation is ascribed greater significance than the curve of calcium carbonate concentration, as this latter is influenced by changes in the rate of accumulation of biogenous silica. If, for instance, the curve of carbonate concentration were used instead of the accumulation curve, the center of substage 3.1 would be placed at 150 cm instead of 160 cm in core 59. This would give (cf. table 2.59.13) $\Sigma\ Ti\,O_2 = 54$, $d = -2$, $\Delta\ d = 10$ ($\approx$ 19 000 years) and $\Delta\ d/d_0 = 0.71$ instead of 0.21. Table 2.59.13 gives a comparison between the values of Σ Ti O_2 (values for the missing top added) found in assumedly equivalent stages and substages of cores 59 and 60. For a detailed explanation of the table, see § 2.58.13 and § 1.2.5. — The lowest correlated unit is the center of the substage 14.2 with a minimum titanium age of $706 \cdot 10^3$ years in core 60 (Σ Ti $O_2 = 374$ mg/cm² at the upper border of the central stratum). The most probable corresponding age value in core 59 is $15 \cdot 10^3$ years less (Σ Ti $O_2 = 366$ mg/cm² at the center of the substage) and the error thus amounts to 2 % of the age value, which is regarded as good. The average deviation of the titanium age found in core 59 from that in core 60 is $\Delta\ d/d_0 = 0.90$, i. e. the average titanium age error amounts to 90 % of the stratigraphical uncertainty. This is considered very satisfactory. In two cases only, $\Delta\ d/d_0$ exceeds 2.0, viz. in stages 6 and 14.

A remarkable facies feature in core 59 is the comparatively high rate of accumulation of calcium carbonate during the substage 8.4, which makes the corresponding rock unit unusually thick. Already in core 58, 220 miles to the north, this substage is distinctly indicated, gets very well developed in core 59 but degenerates markedly in core 60, 90 miles to the south. — If core 59 were to be interpreted without a comparison of cores further to the south and to the north, there would be good reason to designate the substage 8.4 as a stage. The conditions found in core 58 and 60 as well as in 45 and 46 further to the east rather demand the substage definition. This conclusion is also corroborated by the high percentage of *Globorotalia* in the unit in question in core 59.

Core 60

East Eupelagic Area

(North Equatorial carbonate facies)

Station no. 92.

Lat. 1° 35′ N, *Long.* 134° 57′ W.

Depth 4 540 m.

Length of core 1 013 cm.

Topography: No record.

Abstract of interpretation. The station is located below the South Equatorial Current and the sequence records in detail the circulation changes during the last appr. 725 000 years except the very last appr. 7 500 years which correspond to the truncation of the top. The core is remarkable in so far as it displays the greatest changes in calcium carbonate accumulation hitherto recorded, viz. from 32 to 3 830 fors. Another regional maximum, the concentration of radiolaria 133 000/g is found in core 60. — The rate of accumulation of biogenous silica increases in the carbonate maxima, and the diatoms contribute to this component to a greater extent than further north in the Equatorial area. The maximum total rate of accumulation in core 60 amounts to 4.4 kfor which in this case (60—150) corresponds to 6.5 cm/1 000 years (wet sediment). The minimum value (at 60—518) is 136 fors corresponding to 0.54 cm/1 000 years. The size distribution of *Coscinodiscus nodulifer*, the percentage distribution of *Globorotalia*, and the frequency of coccoliths indicate, that the ages 8, 6, 2, and especially 4, were characterized by rates of production and thus presumably by intensities

of atmospheric and oceanic circulation considerably higher than older ages of increased carbonate accumulation. That these older ages have in spite of this a comparatively high rate of carbonate accumulation is believed to depend on the lower maximum rate of dissolution connected to the higher minimum temperature of the deep and bottom water of the ocean.

.1 Calcium carbonate. Chalk ooze and marl ooze alternate, and the changes of carbonate concentration and rate of carbonate accumulation with time, which is typical for the North Equatorial carbonate facies, are repeated in detail in this core. As a result it is suited for correlation purposes. The maximum rate of calcium carbonate accumulation in substage 8.4 has been reduced to 260 fors in this core from 1 620 in core 59. The maximum value in core 60 is 3 830 fors (at 150 cm) which is the highest value hitherto recorded in North Equatorial carbonate facies. The minimum in core 60 is 32 fors (at 408 cm) which is fairly close to the lowest value found in this facies in the East-Central Pacific (21 fors in core 58, 218 and 659 cm). The changes in rate of calcium carbonate accumulation are thus very great, amounting to 120 times the minimum value.

.2 Titanium. The distribution is regular and no marked changes are indicated in the rate of minerogenous accumulation. The maximum total rate of accumulation is 4 400 fors (at 150 cm), corresponding to 6.5 cm wet sediment/1 000 years. The minimum rate is 136 fors (at 517 cm) corresponding to 0.54 cm/1 000 years.

.3 Silica. The percentage of biogenous silica increases markedly in the carbonate minima due to the decreased dilution of the silica with calcareous matter. The simultaneous increase in percentage of clay (titanium) is however several times greater, so that as a matter of fact the rate of accumulation of biogenous silica is appr. four times higher in the carbonate maxima than in the minima.

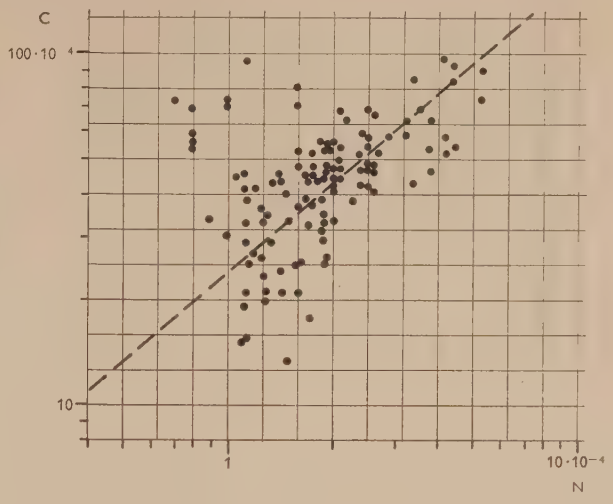

Fig. 2.60.4. Relation between carbon and nitrogen concentrations in core 60. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits.

.4 Organic matter. The correlation carbon-nitrogen is comparatively good (fig. 2.60.4) although there are groups of strongly deviating samples. The distribution of rates of accumulation of carbon and nitrogen (pl. 2.60, col. C and N) demonstrates that the concentration maxima in the marl ooze beds are not caused by an increased rate of accumulation but by a decreased dilution with calcareous matter. The highest rates of accumulation are found in stage 2 (2 600 cfor of carbon and 79 cfor of nitrogen) and are believed not to be caused by extraordinary rates of deposition but by the fact that decomposition has not proceeded very far in the upper strata.

.5 Phosphorus. The increase of phosphate with decreasing carbonate content (fig. 2.60.5) is smaller than normal. This effect is due to extensive dilution of the sediment with biogenous silica. The average rate of phosphorus accumulation is low (61 cfor since stage 5) as compared with the neighbouring cores (71 cfor in core 59 and 109 cfor in core 61).

.6 Colour and pattern. The deposit is (pl. 2.60, col. 1,2, and 3; pl. 2.6.4, 2.6.5, and 2.6.9) as a whole light, the colours ranging between pure white and yellowish brown. Increased

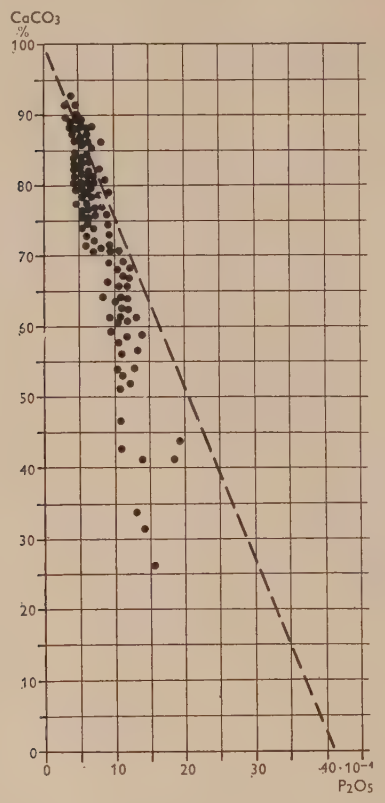

Fig. 2.60.5. Relation between concentration of phosphorus and concentration of calcium carbonate in core 60. The dashed line corresponds to the estimated eupelagic average.

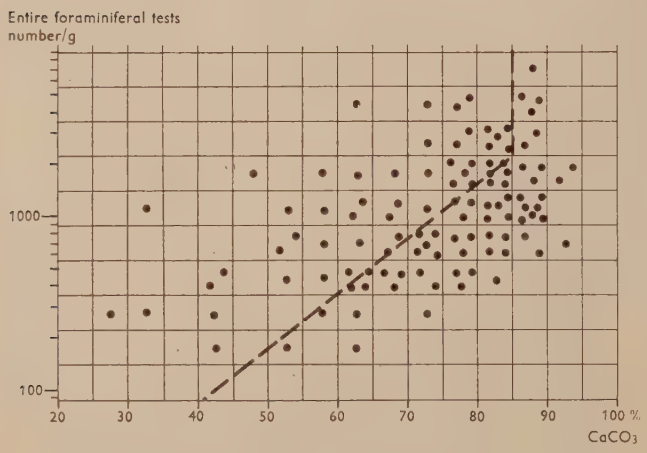

Fig. 2.60.7.1. Relation between concentration of entire foraminiferal tests and percentage of calcium carbonate. The dashed line illustrates the average eupelagic conditions.

High foraminiferal concentrations corresponding to low carbonate concentrations might be explained if it is assumed that the original deposit was rich in coccoliths and that these were the main object of the postdepositional dissolution because of their large surface per unit mass and because of the increased solubility of small calcite grains.

blackness appears to be caused also by factors other than increased content of clay and dark organic matter. Colour values are missing between 236 and 300 cm. Digging structures are frequent and include plough structures, open and filled cavities and channels, sometimes with faecal pellets, which are here pure white. The basal bed contains a few blackish laminae with an internal microlamination. The laminae, which have an increased content of manganese (qualitative test), are sharply confined upwards and diffusely downwards. The lamination is believed to be caused by precipitation of manganese oxides from slowly rising solutions.

.7 *Foraminifera.* There is a comparatively narrow range in the concentration of foraminifera in view of the big changes of the carbonate content (fig. 2.60.7.1). This appears to be due to the addition of carbonate from coccoliths in the production maxima. As a result the »coccolith corner» of the graph in fig. 2.60.7.1 is better developed than in core 59 although not as marked as in core 61 where sample groups very rich in coccoliths have been isolated from the distribution body (fig. 2.61. 7.1).

The linear logarithmic correlation between conc. planktonic foraminifera and conc. benthonic foraminiera (fig. 2.60.7.2) is fairly good, although two samples (372 and 669) deviate strongly. The former deviation is caused by dissolution with coccoliths. The reason for the latter deviation is not known. The planktonic fauna of the greatest part of the sequence is dominated by *Globigerina*, comparatively few strata by *Globorotalia* and only one stratum (lower part of substage 8.2) by *Pulleniatina obliquiloculata*. The *Globorotalia*- maximum in stage 2, which is repeated in most of the equifacial sequences investigated, is unusually high in this core. Several of the odd number stages are in the normal way characterized by maxima in the percentage of *Globorotalia* indicating a decreased rate of upwelling at the

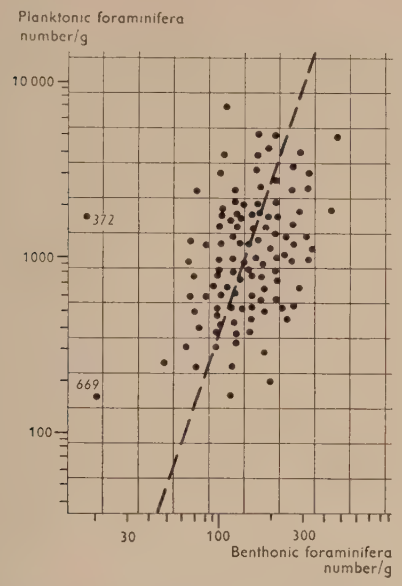

Fig. 2.60.7.2. Relation between concentration of entire tests of planktonic and benthonic foraminifera in core 60. The dashed line corresponds to the estimated eupelagic regression (§ 1.7.2).

The distribution agrees well with the eupelagic average. The deviation of sample 372 is due to dilution with coccoliths. The reason for the deviation of sample 669 is not known.

surface of the ocean. The comparatively high percentages of *Globorotalia* in stages 10 and 12 might possibly indicate that upwelling of cold deep water did not increase as much as during later even-number ages. The same conditions which bring a low rate of upwelling in the divergences are likely to cause an increase of the deep and bottom water temperature (§ 1.1.5) and thus a lowered rate of carbonate dissolution. This is believed to be the cause of the comparatively high rate of carbonate accumulation in the lower stages.

In the graph conc. planktonic foraminiera — percentage of *Globorotalia* (fig. 2.60.7.3) several samples fall outside the normal distribution field. These samples can be divided into two groups, one with comparatively high and one with comparatively low conc. of planktonic foraminifera. The deviation of the first group is caused by the lowering of the foraminiferal concentration through dilution with coccoliths. The second group consists of five samples from those strata, which in spite of their lowered content of calcium carbonate and of planktonic foraminifera, do not display any considerable increase in the percentage of *Globorotalia*. The reason is not understood.

.8 Radiolaria. Especially the stages 3,5, and 7 are very rich in radiolaria and the highest concentration value found in the East Pacific material (133 000 specimens $> 150\,\mu$ per g sediment) originate from stage 5. The maximum values for the rate of accumulation of radiolaria are very high too, viz. 87 400 specimens/cm² · 1 000 years (regional max. 89 000 in core 61). The average rate of accumulation decreases slightly downwards. It is not known whether this is an original or diagenetical feature. The latter alternative appears to be the most probable one as neither the average percentage nor the average rate of accumulation of biogenous silica decrease considerably with increasing depth in the deposit.

.9 Diatoms. The diatoms are well preserved. The changes in size distribution of *Coscinodiscus nodulifer* are almost identical with those found in core 59 and the description given in § 2.59.9 can in all details be applied to core 60. To analyze the phenomenon of the occurrence of big size maxima in the distribution of *Coscinodiscus nodulifer*, a few samples from the stages 3 and 4 were subjected to determination

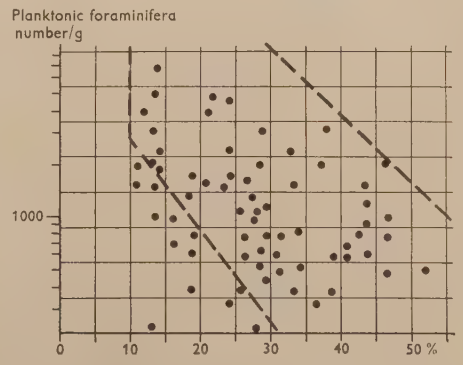

Fig. 2.60.7.3. Relation between concentration of entire tests of planktonic foraminifera and planktonic faunal percentage of *Globorotalia menardii + tumida*. The guide lines coincide roughly with the eupelagic equiprobability curve 0.05, i. e. the probability of occurence of a eupelagic sample outside these boundaries is less than 10 percent.

of the concentration and rate of accumulation of this diatom as well as its absolute frequency distribution. The results are treated in detail in chapter 1.9 but the total number of frustules accumulated per cm² in 1 000 years might be quoted here (table 2.60.9).

TABLE 2.60.9.

Sample no.	Rate of accumulation (number of frustules of *Coscinodiscus nodulifer*/cm² · 1 000 years)
60—229	277 000
60—240	302 000
60—257	308 000
60—279	1 014 000
60—298	2 438 000

The maximum value appears to be surpassed by stage 4 in core 61, but no counts are available from this.

.10 — .11 Other fossils, rock fragments and mineral grains. Single occurrences of fish teeth are frequent. Single grains of pumice and palagonite were found in a few samples. Manganese micronodules occur in low concentrations only.

.12 Diagenesis. The average strength is lower than in core 51 from appr. 2 to 8 m and joins the average curve for this core below and above these limits. Due to the brecciation caused by bottom scavengers and possibly to a strength stratification, the strength values scatter considerably. The correlation calcium carbonate — salinity is of interest as it indicates a high salinity of the carbonate-free matter. This is believed to be due to the comparatively big quantities of colloidal silica present which increase the capacity of the deposit to retain sea water.

In the carbonate minima the foraminifera and radiolaria are often etched and the foraminifera are in all samples often recrystallized and filled or half filled.

.13 Stratigraphy. The truncation of the top is estimated to correspond to an amount of TiO_2 of 4.0 mg/cm² or to 7 500 years. This estimate is based on a correlation of the present top surface with a level situated somewhere between 17 and 21 cm in core 61 B. The stratigraphy of core 60 has been used as a standard at the evaluation of the eupelagic carbonate sequences and a detailed description and interpretation is found in § and table 2.59.13.

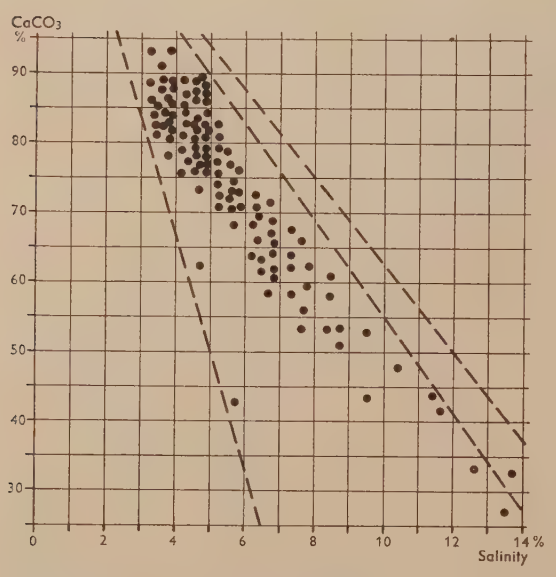

Fig. 2.60.12. Relation between calcium carbonate content and salinity in core 60. The dashed lines correspond to lines A, B and C in fig. 1.12.2.1 and 1.12.2.2.

Core 61

East Eupelagic Area

(Equatorial Divergence subfacies)

Station no. 93.

Lat. 0° 06′ S. *Long.* 135° 58′ W.

Depth 4 437 m.

Length of core 61; 1 029 cm, core 61 B; 45 cm.

Topography: No record.

Abstract of interpretation. The station is located below the Equatorial Divergence and as a result a comparatively high rate of accumulation of biogenous matter appears to have been maintained even in the accumulation minima. This gives rise to difficulties in carrying out the correlation, especially of stratigraphical units older than appr. 270 000 years.

The maximum total rate of accumulation is 4 080 fors, corresponding to slightly more than seven cm of wet sediment per 1 000 years. Due to the high average rate of accumulation in stage 4, this unit is unusually thick, viz. 270 cm. The minimum in stage 7 is very faint but the minimum in substage 8.3 on the other hand is more marked than usual. The agreement between the rate of minerogenous accumulation in cores 60 and 61 was tested down to stage 6 and was found to be good (average deviation 39 % of the content of the central stratum). Below stage 6 continued approximate agreement is supposed and used as an additional aid to the correlation.

The titanium content of core 61 B has been calibrated in terms of absolute age by means of radiocarbon age determination.

Coccoliths are abundant in some strata of core 61 and in one case form an 80 % coccolith ooze. It is not known whether the high rate of coccolith accumulation is due mainly to a high rate of production or to a low rate of dissolution.

.1 *Calcium carbonate.* The sequence consists of chalk ooze with a few intercalated marl ooze strata. The maximum rate of calcium carbonate accumulation is 3 270 fors (at 190 cm) and the average is high throughout the sequence. The minimum value, 124 fors, is found at 650 cm. The biggest change in rate of carbonate accumulation is thus only 26.4 times the minimum value. The corresponding factor in core 60 is more than four times bigger (120). The constantly high accumulation is a facies feature which is believed to depend on the location of the station below the Equatorial Divergence. The comparatively small changes in the rate or accumulation give rise to some ambiguity at the correlation of the lower stages represented in this core. — Microscopical investigation shows that coccoliths play an important part in the accumulation of calcium carbonate. In one case (560—570 cm), almost 100 % of the carbonate accumulation (960—1 130 fors) is due to coccoliths (cf § 2.61.7).

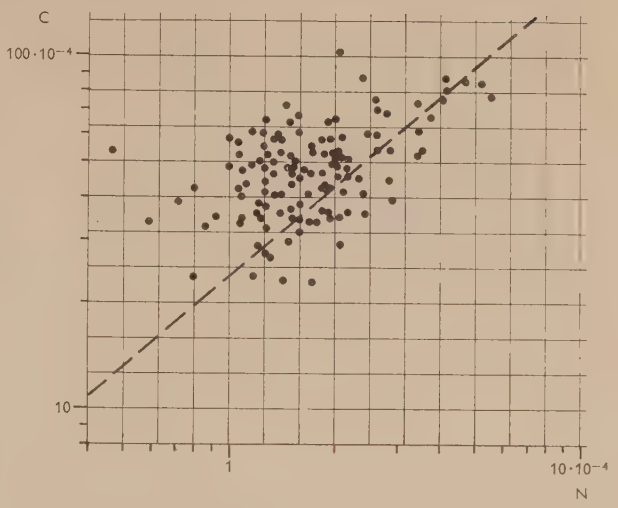

Fig. 2.61.4. Relation between carbon and nitrogen concentrations in core 61. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits.

.2 *Titanium.* The distribution is regular and the concentrations are generally very low on account of the high average rates of accumulation of carbonate and biogenous silica. The concentrations indicate a minimum total rate of accumulation of 264 fors (at 650 cm) and a maximum value of 4 080 fors (at 410 cm) corresponding to 0.87 resp. 7.05 cm wet sediment per 1 000 years. The average rate of accumulation is 2.13 cm/1 000 years.

.3 *Silica.* On account of the increased dilution with calcium carbonate the percentage of biogenous silica is depressed in the carbonate maxima in spite of the increased rate of accumulation of silica. This rate is generally high especially in the maxima of total rate of accumulation, and attains the highest value in stage 4, viz. 860 fors.

.4 *Organic matter.* In spite of the secondary decomposition the accumulation of carbon and nitrogen attains comparatively high values in stage 4 (2 200 cfor carbon, 81 cfor nitrogen), which is in agreement with the very high biogenous production of calcium carbonate and silica during this age. The distribution

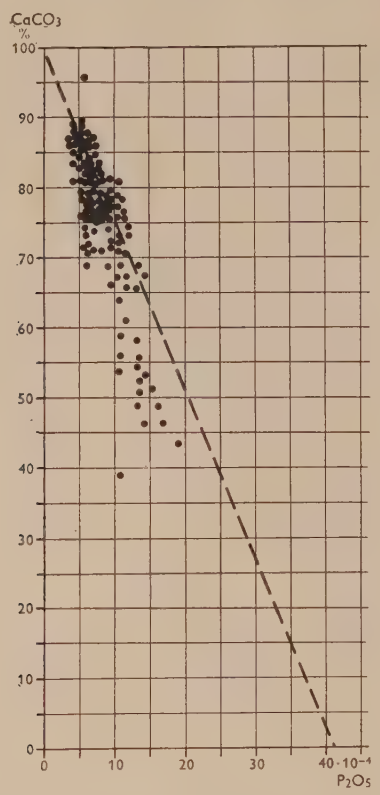

Fig. 2.61.5. Relation between concentration of phosphorus and concentration of calcium carbonate in core 61. The dashed line corresponds to the estimated eupelagic average.

of the samples in the C—N diagram (fig. 2.61.4) agrees fairly well with the average regression for calcium carbonate sediments, with an overweight in samples abnormally rich in carbon.

.5 Phosphorus. From fig. 2.61.5 it appears that samples low in carbonate are abnormally low in phoshporus. That this is entirely due to dilution with biogenous silica is seen from fig. 1.5.4.3. With regard to their clay content most samples are rich in phosphorus, and the rate of accumulation of phosphorus is very high (average 109 cfor above stage 5), especially in stage 4 (pl 2.61, col. P_2O_5).

.6 Colour and pattern. Great parts of the column are pure white and blackness values higher than *g* are rare. The blackness appears mainly to depend on the carbonate content of the deposit but a few dark strata appear in the carbonate-rich sediment of stage 4. In this case the black pigment disappears at oxidation and is believed to be of organic origin. The deposit is rich in all kinds of digging structures (pl. 2.6.5 and 2.6.9). On account of the comparatively high rate of deposition in the even number stages the original layer boundaries have not been completely reworked and can still be traced in some cases. Microlamination caused by secondarily precipitated manganese oxidates, occurs in several strata.

.7 Foraminifera. In spite of the high calcium carbonate content the concentration of foraminifera varies strongly, viz. from a few to more than ten thousand individuals/g. This is due to the extraordinarily great amounts of coccoliths, which occur in such abundance in the stratum 570—560 cm that the deposit is an 80 % coccolith chalk ooze with a few percent of clay and the rest silica, mainly in the form of diatom frustules. In the correlation diagram conc. foraminifera — conc. $CaCO_3$ (fig. 2.61.7.1), samples rich in coccoliths are easily traced as they collect in the right lower edge of the normal distribution field, immediately below it, or, in extreme cases, far down in the right corner of the graph. These conditions cause a marked scattering also in the correlation conc. planktonic foraminifera: conc. benthonic foraminifera (fig. 2.61.7.2). This is easily understood as the variation in concentration of foraminiferal plankton has another significance than in sequences relatively poor in coccoliths. Very high rates of accumulation of benthonic foraminifera occur (1 540 specimens/cm² · 1 000 years) and as usual the maximum is situated in stage 4, where the deposition of food appears to have been unsurpassed. As a comparison it may be mentioned that the highest value found in other cores is 610 specimens/cm² · 1 000 years (core 59, 40 cm). The fact that strata consisting of globorotalia ooze are thin and scarce confirms the view that the high production recorded took place in surface water of a low temperature

(caused by the upwelling in the Equatorial Divergence). The apparently significant *Globorotalia* — maximum in stage 2 is repeated in this core. The faunal composition in stage 8 indicates that low-temperature conditions were not as extreme as during later accumulation-maximum ages. An explanation of the high rates of accumulation in the lower stages has been suggested in § 1.1.5.

Due to the abundance of coccoliths, the distribution field in the correlation graph conc. planktonic foraminifera — percentage of *Globorotalia* (fig. 2.61.7.3) has been displaced vertically but the correlation between the two properties is still fairly good.

.8 Radiolaria. On account of the increased dilution with carbonate and diatomaceous silica the concentration of radiolaria does not attain the peak values recorded in core 60. The rate of accumulation of radiolaria, however, reaches the regional maximum value in the unique stage 4 with 89 000 individuals/cm² · · 1 000 years. The reason for the marked drop in the rate of accumulation in the lowest part of stage 4 is not known.

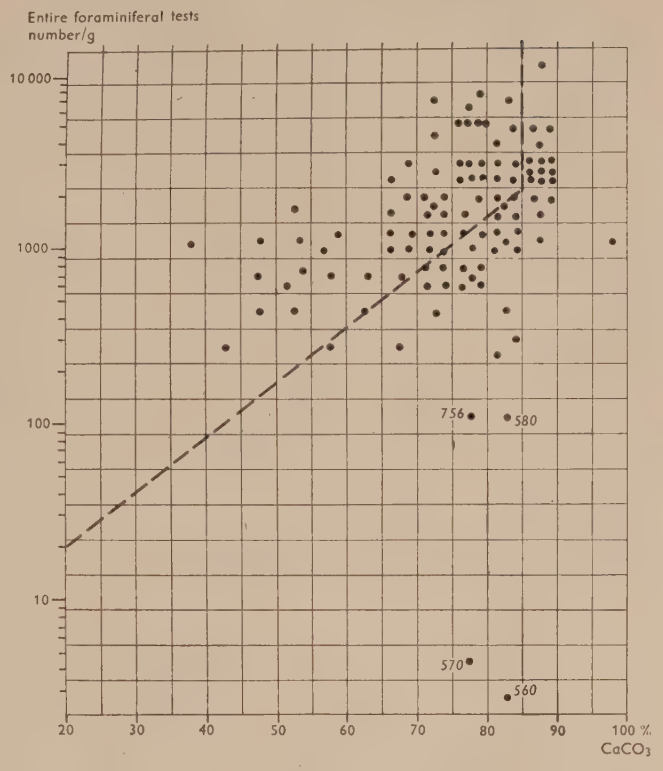

Fig. 2.61.7.1. Relation between concentration of entire foraminiferal tests and percentage of calcium carbonate. The dashed line illustrates the average eupelagic conditions.

Samples 560, 570, 580 and 756 are exceptionally rich in coccoliths. Abnormally high concentrations of entire tests with regard to the carbonate content are probably due to enrichment of foraminifera by dissolution of coccoliths (cf. fig. 2.60.7.1).

.9 Diatoms. The frustules are in a very good state of preservation and the sequence is well suited for a study of the size frequency distribution of *Coscinodiscus nodulifer*. The circumstance that very extreme conditions of low rate of accumulation do not prevail even in the accumulation minima in the facies type represented by core 61, tends to reduce the amplitude also in the size distribution changes of *Coscinodiscus nodulifer*. As a result the big size maxima do often continue, although not with very high frequencies, through stages of lowered rate of accumulation. The big size maximum in stage 2 is very well developed and in substage 3.2 the maximum, which was only faintly indicated in core 59 and 60, is distinct. As usual the most marked big size maximum is that of stage 4 which starts already in upper stage 5 and continues into stage 3. The maximum of stage 6 extends down into 7 and up into 5, and that of substage 8.2 can be traced already in 8.3. Especially stage 4 is very rich in frustules and the rates of accumulation quoted in § 2.60.9 are estimated to be surpassed.

.10 Other fossils. In spite of the high total rate of accumulation, occurrences of fish teeth are more frequent than in neighbouring cores, indicating that the accumulation of teeth is comparatively high (order of magnitude 10—20 per cm² in 1 000 years).

.11 Rock fragments and mineral grains. A few fragments of pumice and massive glass per gram occur sporadically. The concentration of manganese micronodules is likewise low.

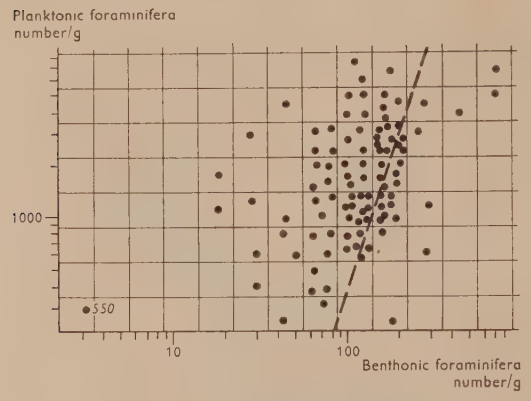

Fig. 2.61.7.2. Relation between concentration of entire tests of planktonic and benthonic foraminifera in core 61. The dashed line corresponds to the estimated eupelagic regression (§ 1.7.2).

The scattering of the values to the left is due to a high rac of coccoliths. No general explanation has been found of the abnormally high benthos values.

.12 Diagenesis. The strength does not increase markedly above stage 5. The rate of increase with depth below this stage is considered normal. As in core 60, the salinity of the carbonate-free material is high, probably due to the presence of colloidal silica.

The foraminifera are often partly recrystallized and seldom show traces of corrosion.

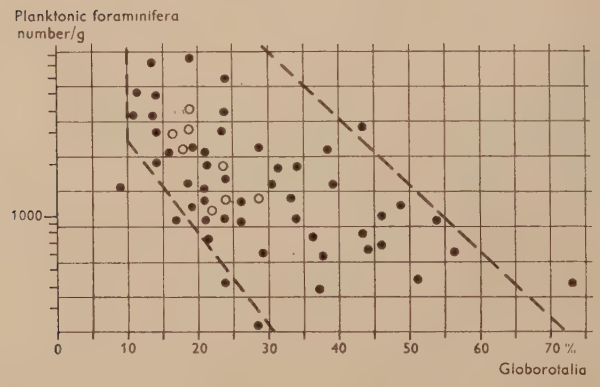

Fig. 2.61.7.3. Relation between concentration of entire tests of planktonic foraminifera and planktonic faunal percentage of *Globorotalia menardii + tumida*. The guide lines coincide roughly with the eupelagic equiprobability curve 0.05, i. e. the probability of occurrence of a eupelagic sample outside these boundaries is less than 10 percent.

Open circles correspond to samples from core 61 B. Dilution with coccoliths is believed to cause the general depression of foraminiferal concentrations corresponding to low percentages of *Globorotalia*.

Radiolaria and diatoms are in a perfect state of preservation.

.13 Stratigraphy. The present truncated top level is correlated with a level located somewhere between 23 and 29 cm in core 61 B. Thus the top layer missing in core 61 has a titanium content of appr. 5.4 mg/cm² which corresponds to slightly more than 10 000 years. Core 61 B is of special interest as it is the best record obtained of the top layer in Equatorial carbonate facies. On account of the high total rate of accumulation and the high carbonate content, this core is also the most suitable one for dating by means of radioactive carbonate carbon. A radiocarbon age determination (ARRHENIUS, KJELLBERG and LIBBY, 1951) gave as result 14 200 years ± 900 for the lower boundary (45 cm) of 61 B. The titanium content of the column is 7,59 mg/cm² and thus 10 000 years correspond to 5.35 mg Ti $O/_2$cm². This calibration is used for all other transformations of titanium time units to calendary units. — It is interesting to note the lowered carbonate accumulation of the present time and of the stratum appr. 22—16 cm (Σ TiO_2 = 4.8 — 2.4 mg/cm²) corresponding to 9 000—4 500 years.

Owing to the low contrasts in rate of carbonate accumulation, difficulties arise in the determination of the center of some substages, e. g. 3.2 and of all stages below 6, which are in this subfacies not identifiable by their relative amplitudes. The titanium ages of the centers of stratigraphical units younger than 6 have been collected in table 2.61.13. From this it is seen that the agreement with core 60 is very good except in substage 4.2 where $\Delta\, d/d_0 = 1.33$. The deviation decreases to — 0.17 if the center of 4.2 is placed at 370 cm instead of 410 cm. Such a location is quite possible but could not be guessed a priori and has therefore not been entered in the table. The average value of the titanium age deviation is 0.38, and 0.20 if the value for substage 2.2 is not taken

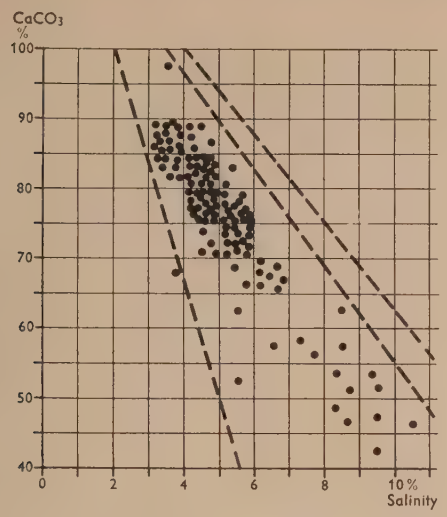

Fig. 2.61.12. Relation between calcium carbonate content and salinity in core 61. The dashed lines correspond to lines A, B and C in fig. 1.12.2.1 and 1.12.2.2.

into account. The age of the center of the lowest unit recorded in the table, stage 5, exceeds the highest possible value in core 60 by 11 mg TiO_2/cm or 8 % of the age, which is in core 60 estimated to be $266 \cdot 10^3$ years.

At the correlation of units older than stage 5, continued approximate constancy of the minerogenous accumulation has been postulated and the titanium ages, extrapolated below stage 5, have been used as an aid. The most remarkable features of these older strata are that stage 7 is corresponded by an unusually low and substage 8.3 by an unusually high decrease in the rate of calcium carbonate accumulation. The *Coscinodiscus* distribution is believed to confirm the interpretation of the stratigraphy of the lower strata. The lowest level represented in core 61 has an estimated age of $485 \cdot 10^3$ years.

Core 62

East Eupelagic Area

(South Equatorial carbonate facies)

Station no. 94.

Lat. 3° 00′ S, *Long.* 136° 26′ W.

Depth 4 510 m.

Length of core 1 479 cm.

Topography: In the neighbourhood of the station the bottom was level. 11 km to the south an interesting type of topography was found (fig. 2.62.0). The bottom sloped down

TABLE 2.61.13

1	2	3	4	5	6	7	8	9	10	11
	Core 60					Core 61				
Stage or Substage no.	Depth, cm		Σ TiO_2 mg/cm²		TiO_2-content of central stratum, mg/cm² = d_0	Depth, cm	Σ TiO_2 mg/cm²	Σ TiO_2 (core 60) — — Σ TiO_2 (core 61) = d	Stepwise change in d mg TiO_2/cm² = Δd	$\frac{\Delta d}{d_0}$
	Borders of central stratum	Center of central stratum	Borders of central stratum	Center of central stratum		Center of central stratum				
2.2	109 181	150	23 32	27	9	150	33	— 6	— 6	0.67
3.1	205 225	215	44 58	52	14	250	57	— 5	+ 1	0.07
3.3	249 264	257	66 77	75	11	322	82	— 7	— 2	0.18
4.2	288 308	298	85 91	88	6	410	103	—15	— 8	1.33
4.4	338 365	361	103 114	112	11	550	126	—14	+ 1	0.09
5	400 412	408	135 144	141	9	650	155	—14	0	0.00
										m = 0.38

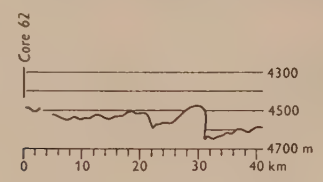

Fig. 2.62.0. Bottom topography in the vicinity of the station of core 62. Redrawn from Koczy (contribution to vol. IV).

90 m in 600 m, then slowly rose again 130 m in 5 km after which it fell abruptly 180 m and finally rose slowly again. These features possibly correspond to a series of fault scarps.

Abstract of interpretation. No. 62 is the longest core of the East Pacific material. It penetrates into Upper Pliocene to an age level of appr. 1.6 million years, and does not, therefore, extend as far back in time as core 58 which comprises appr. 2.5 million years. The upper Pleistocene strata can be directly correlated with equivalent members in core 60 e. a. The amount of titanium accumulated since the oldest correlated age is in good agreement with the corresponding accumulation in core 60. Although the average titanium age error is less than the time included in the correlated central stratum, deviations occur which are considered great in comparison with those found in the cores 59 and 61. A stratigraphical subdivision is carried out of the Pliocene top strata and the lowest Pleistocene strata and these units are tentatively correlated with equivalent members in core 58.

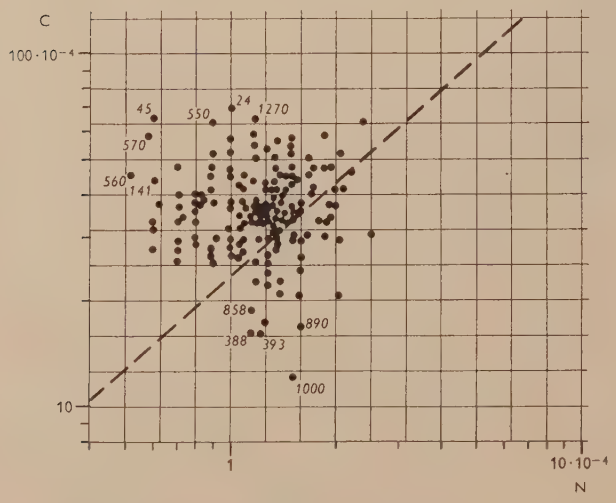

Fig. 2.62.4. Relation between carbon and nitrogen concentrations in core 62. The dashed line corresponds to the estimated average of the calcareous East Pacific deposits.

The substage 8.6 is remarkable insomuch as it displays the highest rate of total accumulation (8 930 fors or 8.0 cm/1 000 years) and of calcium carbonate accumulation (8 230 fors) recorded in the East Pacific. These high values appear to be due to a slightly increased circulation and carbonate production at the ocean surface without a very extensive increase in the rate of dissolution.

.1 Calcium carbonate. The Upper Pleistocene is very rich in calcium carbonate in this core and since stage 5 only chalk ooze has been deposited. All main stages and several substages are recognizable down to substage 8.4. Very high calcium carbonate values are found in substage 8.6, viz. as a maximum 8 230 fors $CaCO_3$. This is the highest value recorded in the East Pacific material. The minimum value in core 62, 75 fors, is found in stage 5. In the Pliocene part of the sequence the rate of calcium carbonate accumulation does not exceed 780 fors.

.2 Titanium. The distribution is regular and as far down as comparative stratigraphical correlation permits a control (to substage 8.4), good agreement with core 60 with regard to the rate of accumulation of titanium is found. The titanium content indicates a very high total rate of accumulation in substage 8.6, viz. 8 930 fors, which is the highest value recorded in the East Pacific and corresponds to 8.0 cm of wet sediment/1 000 years.

.3 Silica. The average content of biogenous silica is appr. 8 % in the Pleistocene part of the sequence and increases more than twice in the basal beds (Pliocene). Petrographical dominance of silica is not attained in any part of the sequence.

.4 Organic matter. As a whole the deposit is fairly poor in organic matter. In the corre-

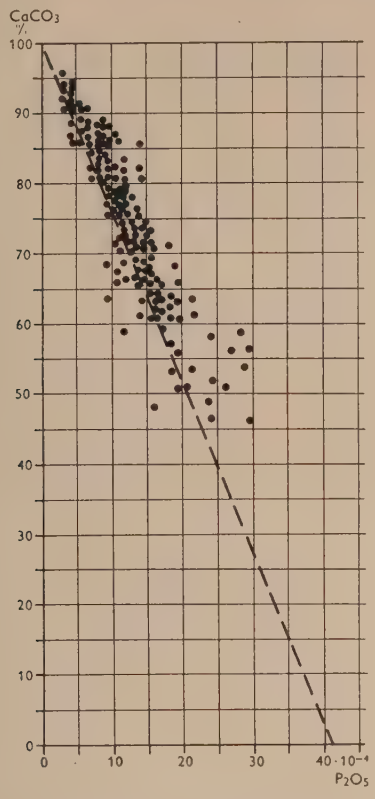

Fig. 2.62.5. Relation between concentration of phosphorus and concentration of calcium carbonate in core 62. The dashed line corresponds to the estimated eupelagic average.

lation diagram C—N (fig. 2.62.4) the samples tend to concentrate slightly above the average regression line for calcareous facies. There is no correlation between carbon and nitrogen. The most strongly deviating samples rich in carbon and poor in nitrogen are indicated $A+$ in pl. 2.62, col. C. They are all derived from carbonate maxima, viz. from stages 2 and 10, substage 3.2, and an unlabelled subordinate maximum in the Pliocene part of the sequence. Samples abnormally poor in carbon are indicated $A-$ in pl. 2.62. No general explanation can be found for their distribution. The most significant case, where two abnormal values are found in subsequent samples, is, however, connected to a carbonate minimum (stage 9). The general tendency of the high C/N ratios to appear in connection with a high content of $CaCO_3$ is discussed in chapter 1.4.

The maximum values of rate of accumulation of organic matter in this core are found in substage 8.6 and amount to 2 220 cfor carbon and 62 cfor nitrogen.

.5 Phosphorus. From the distribution shown in fig. 2.62.5 it is evident that in view of the carbonate content most samples are rich in phosphorus. In fig. 1.5.4.2 the samples from core 62 do not, however, deviate markedly from the average distribution. It is therefore concluded that the distribution of the samples rich in carbonate to the right of the guide line in fig. 2.62.5 is due to the unusually low dilution with biogenous silica.

The rate of accumulation of phosphorus is appr. the same as in core 60 (average 60 cfor above stage 5) and is thus low in comparison with core 61 (109 cfor).

.6 Colour and pattern. The average hue of the deposit is more yellowish (3) in the Pliocene and lower Pleistocene beds than in the upper Pleistocene beds, which are on an average more reddish (4). The most marked stratification with regard to the colour is connected to the extensive changes in carbonate content in the middle and upper Pleistocene. The deposit is very rich in all sorts of digging structures (pl. 2.6.5 and 2.6.10).

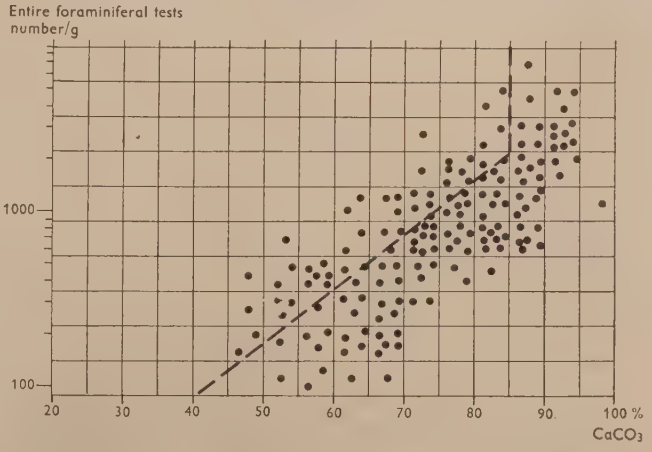

Fig. 2.62.7.1. Relation between concentration of entire foraminiferal tests and percentage of calcium carbonate. The dashed line illustrates the average eupelagic conditions.

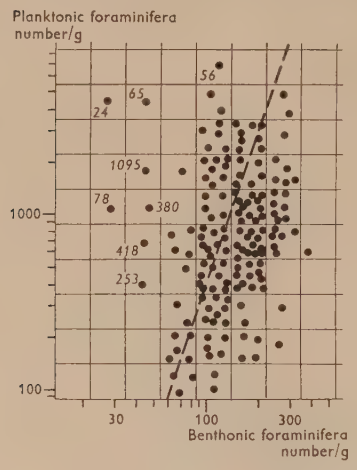

Fig. 2.62.7.2. Relation between concentration of entire tests of planktonic and benthonic foraminifera in core 62. The dashed line corresponds to the estimated eupelagic regression (§ 1.7.2).

The effect of secondary enrichment of benthos is marked in low foraminiferal concentrations. Several, but not all of the values abnormally low in benthos can be explained by dilution with coccoliths.

.7 *Foraminifera.* The correlation between conc. entire foraminifera and conc. $CaCO_3$ is good (fig. 2.62.7.1) and the regression line is situated lower than the East Eupelagic average. There are two reasons for this; firstly the comparatively high content of coccoliths in some of the Pleistocene carbonate maxima, and secondly the comparatively extensive fragmentation in the Pliocene beds. The former effect is most marked in the high, the latter in the low carbonate contents. The main reason for the low average integrity index (entire tests/fragments) in the Pliocene is believed to be the low average rate of deposition, not an increased benthonic activity, as the rate of accumulation of benthonic foraminifera is not higher than in the Pleistocene. The main group of samples displays a comparatively good correlation between conc. plankton and conc. benthos but there are some widely deviating samples which are abnormally poor in benthos. Several of these samples are derived from stage 2 but no general explanation to the anomalies has been found.

The inverse relationship between conc. planktonic foraminifera and percentage of *Globorotalia* is well established in this core and the average increase in the percentage of *Globorotalia* with a decreasing logarithm of the plankton concentration is higher than usual. — The Pliocene beds are almost entirely dominated by *Globorotalia*, which is assumed to indicate a low rate of upwelling and warm surface water. Another typical feature of the Pliocene beds is the comparatively high percentage of *Sphaeroidinella dehiscens*. At the Pliocene-Pleistocene boundary as defined in the present work ($\Sigma TiO_2 = 527$ mg/cm²) the genus *Globigerina* attains dominance which is continued through the Pleistocene beds, interrupted in two early Pleistocene strata, in the minimum stages 13, 11, and 3, in the *Globorotalia* — maximum of stage 2, and in a composite bed extending from stage 9 to 5. At the transition from Pliocene to Pleistocene the percentage of *Sphaeroidinella dehiscens*, is also markedly decreased to values close to

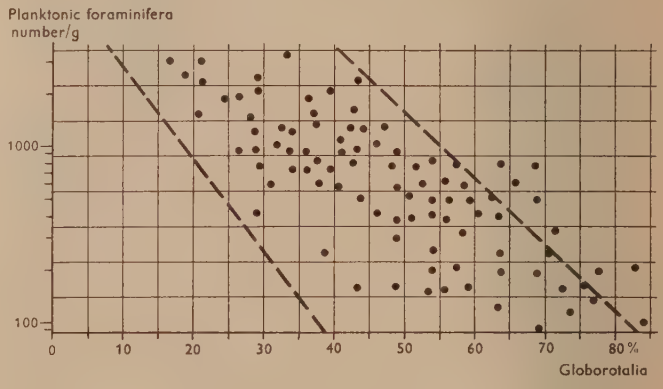

Fig. 2.62.7.3. Relation between concentration of entire tests of planktonic foraminifera and planktonic faunal percentage of *Globorotalia menardii + tumida*. The guide lines coincide roughly with the eupelagic equiprobability curve 0.05, i. e. the probability of occurrence of a eupelagic sample outside these boundaries is less than 10 percent.

The unusually good relationship between the two properties is due mainly to the presence in low foraminiferal concentrations of a comparatively great amount of Pliocene samples. These are not very strongly affected by dissolution, and their planktonic assemblages therefore appear to have retained much of the original high percentage of *Globorotalia menardii + tumida*.

zero whereas *Sphaeroidina bulloides* continues to be represented by a few percent. In the upper Pleistocene there is a conspicuous increase in *Pulleniatina obliquiloculata*.

8. Radiolaria. The rate of accumulation of radiolaria is comparatively low. Since lower stage 14 were accumulated 1 760 000 individuals per cm², whereas in core 60 during the same time 7 687 000 skeletons were accumulated per cm², the former value being 4.4 times lower than the latter. In core 62 the rate of accumulation of radiolaria tends to be high in the lowest Pliocene beds represented, in the Low Intermediate, and in the High Upper Pleistocene. The reason for these changes is not known.

.9 Diatoms. The size distribution of *Coscinodiscus nodulifer* was investigated down to stage 11 (fig. 2.62.9). The distribution changes are much more diffuse than in the North Equatorial carbonate facies but the main large size maximum in stage 5—4 is still traceable as well as the maximum in stage 2, the former as an extension of the tail of the distribution body. The lower maxima in stage 8 and 6 are not clearly separated. In substage 8.6, which is characterized by an extraordinarily high rate of calcium carbonate accumulation, there is a clear tendency of the small size (40 μ) maximum to shrink and of the right tail wedge of the distribution body to swell but this process does not advance as far as in the stages 4 and 2. This indicates that the main factor responsible for the high rate of accumulation in 8.6 is a lowered rate of dissolution rather than an extensively increased rate of production.

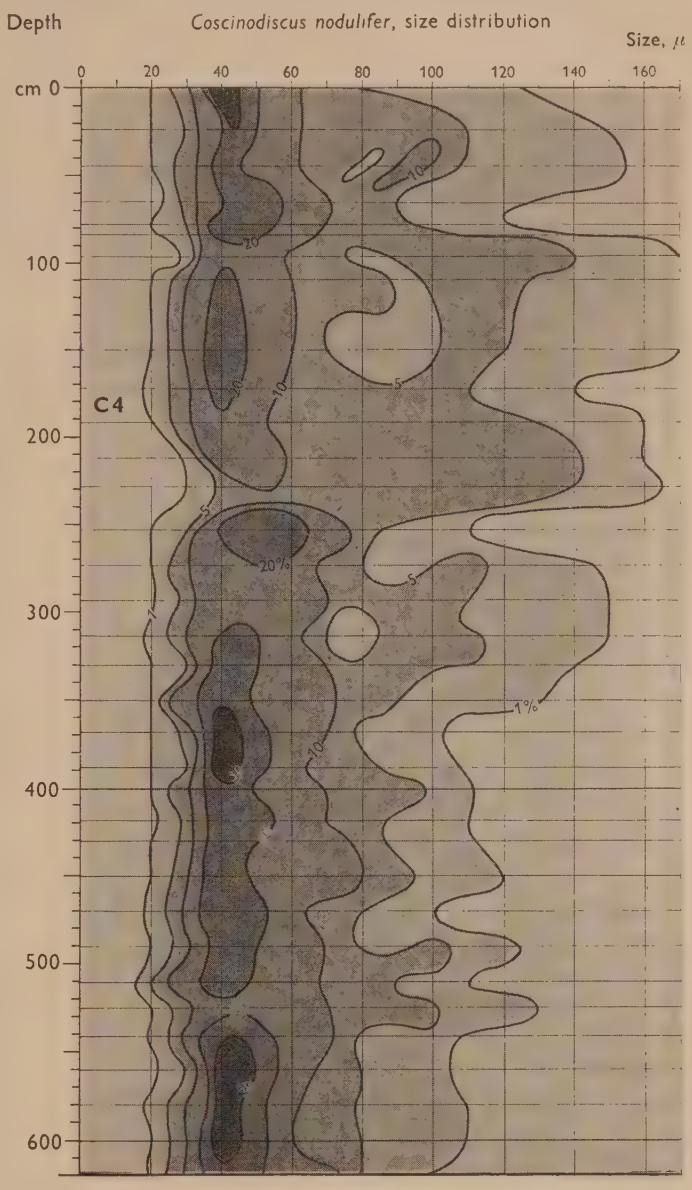

Fig. 2.62.9. Size frequency distribution of *Coscinodiscus nodulifer* in upper part of core 62.

.12 Diagenesis. The average strength is considerably lower than the average of core 51. The average rate of increase in strength with depth is regarded as normal down to approx. 10 m after which the rate is reduced. It is not known whether this reduction is normal or abnormal as this core is the only one considerably exceeding 10 m in length. Abnormally strong induration occurs in three strata. Two of these, located in the intercept 600—400 cm, are corresponded by conspicuous minima in the concentration of radiolaria. Dissolution or

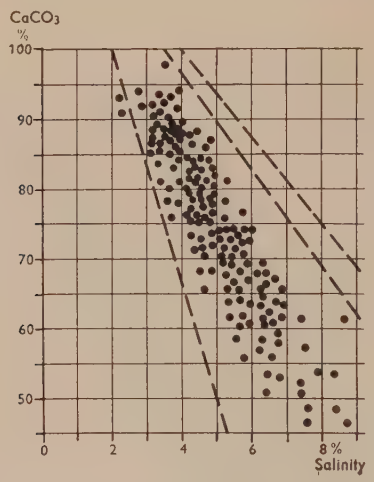

Fig. 2.62.12. Relation between calcium carbonate content and salinity in core 62. The dashed lines correspond to lines A, B and C in fig. 1.12.2.1 and 1.12.2.2.

peptization of these and subsequent cementation of the deposit with colloidal silica is believed to be the reason of the high strength in these cases. The reason for the abnormally extensive induration occurring in stage 2 is not known. The salinity is well correlated with the carbonate content and the regression indicates an intermediate salinity of the carbonate-free material.

Thin sections of material from substage 8.2 were prepared and from the Pliocene carbonate minimum at 1 430 cm. Corrosion of foraminifera and radiolaria was found to be more extensive in the latter case.

.13 Stratigraphy. Owing to the great length and penetration of the corer the truncation of the top is more extensive than usual. The top layer lost is estimated to correspond to a minimum titanium content of appr. 7 mg/cm² TiO_2 and not more than 9 mg/cm² (appr. 40—50 cm). The former value has been applied as a correction.

The change of facies from North Equatorial to South Equatorial carbonate type has brought about marked changes in the relative amplitudes of the curve of rate of carbonate accumulation, and therefore also in the relative thickness of the strata. Stages younger than 8 are looked upon as recognizable by means of qualitative comparison with the North Equatorial sequences. Below substage 8.2 considerable ambiguity would be inherent in a correlation based only on such comparisons and the extrapolated titanium age has therefore been used as an aid in the judgement of the stratigraphical subdivision. The calculated titanium ages of the centers of stages and substages in core 62 are shown and compared with corresponding values from core 60 in table 2.62.13. From this is seen that fairly big deviations occur but the sign of Δd is reversed several times. Thus there is no systematical error involved, e. g. a permanent difference in the rate of deposition in the localities. The main reason for abnormal deviations, such as in stage 6, are believed to be that, on account of the difference in facies, the subordinate stratigraphical units within a stage do not have proportional accumulation amplitudes in the two localities. The level looked upon as the center of the stage in core 60 might thus not be exactly equivalent to that which, by means of qualitative comparison, was judged to be the stage center in core 62. In the case of stage 6 the stage center might under such conditions equally well be situated at 283 cm as at 263 cm. In the former case Δd would be 2 instead of 22 and $\Delta d/d_0 = 0.40$ instead of 4.40 (alternative values in brackets in table 2.62.13). This also would change $\Delta d/d_0$ in stage 7 from -1.18 to 0.64. If these considerations are taken into account the average age deviation in core 62 is 67 % of the age content of the central stratum. If not, the average rises to 92 %. The last value is also regarded as satisfactory.

With the aid of the titanium age (pl. 2.62) extrapolated below the checked part of the sequence, a tentative correlation with core 58 has been carried out in the lowest Pleistocene strata and the top of the Pliocene (stage 20 pl. 2.62, col. $CaCO_3$). Further extension of the correlation has better to be postponed until a few cores penetrating into upper Pliocene are available as links between cores 58 and 62.

TABLE 2.62.13

1	2	3	4	5	6	7	8	9	10	11
	Core 60					Core 62				
Stage or Substage no.	Depth, cm		$\Sigma Ti O_2$ mg/cm²		TiO_2-content of central stratum, mg/cm² = d_0	Depth, cm	ΣTiO_2 mg/cm²	ΣTiO_2 (core 60) — — ΣTiO_2 (core 62) = d	Stepwise change in d mg TiO_2/cm² = Δd	$\frac{\Delta d}{d_0}$
	Borders of central stratum	Center of central stratum	Borders of central stratum	Center of central stratum		Center of central stratum				
2.2	109 181	150	23 32	27	9	56	23	+ 4	+ 4	0.44
3.1	205 225	215	44 58	52	14	110	56	— 4	— 8	0.57
3.2	225 249	235	58 66	64	8	131	66	— 2	+ 2	0.25
3.3	249 264	257	66 77	75	11	172	97	—22	—20	1.82
4.2	288 308	298	85 91	88	6	200	109	—21	+ 1	0.17
4.4	338 365	361	103 114	112	11	220	119	— 7	+14	1.27
5	400 412	408	135 144	141	9	243	139	+ 2	+ 9	1.00
6	479 495	487	175 180	177	5	263 (283)	153 (173)	+24 (+4)	+22 (+2)	4.40 (0.40)
7	507 520	517	185 196	195	11	293	184	+11	—13 (+7)	1.18 (0.64)
8.2	520 545	527	196 210	199	14	313	192	+ 7	— 4	0.29
8.4	562 618	588	220 247	233	27	380	237	— 4	—11	0.41
8.6	644 665	651	260 269	264	9	460	257	+ 7	+11	1.22
9	666 674	669	275 284	282	9	510	272	+10	+ 3	0.33
10	680 760	725	285 306	296	21	550	282	+14	+ 4	0.19
11	775 795	790	313 326	324	13	640	318	+ 6	— 8	0.62
12.2	810 830	820	330 335	332	5	670	332	0	— 6	1.20
12.4	847 865	859	338 346	342	8	695	340	+ 2	+ 2	0.25
13	880 900	890	351 357	354	6	730	358	— 4	— 6	1.00
										m = 0.92 (0.67)

References

ARRHENIUS, G. 1950. Carbon and nitrogen in subaquatic sediments. — Geochimica et Cosmochimica Acta *1*, p. 15—21.

ARRHENIUS, G., KJELLBERG, G. and LIBBY, W. F. 1951. — Age determination of Pacific chalk ooze by radiocarbon and titanium content. — Tellus *3*, p. 222—229.

KUENEN, PH. H. 1950. Marine geology. — Ld. & N. Y.

MELLIS, O., 1949. Yttrande med anledning av G. Arrhenius föredrag om Svenska Djuphavsexpeditionens material. — Geol. Fören. Stockholm Förhandl. 71, p. 200—201.

RIEDEL, W. R., 1952. Tertiary Radiolaria in Western Pacific sediments. — Medd. Oc. Inst. Göteborg, 19.

RITTMAN, A. 1936. Vulkane und ihre Tätigkeit. — Stuttgart.

ZO BELL, C. and ANDERSSON, D. Q. 1936. Vertical distribution of bacteria in marine sediments. — Bull. Am. Ass. Petrol. Geol. *20*, p. 258—269.

REPORTS OF THE SWEDISH DEEP-SEA EXPEDITION. VOL. V
SEDIMENT CORES FROM THE EAST PACIFIC

PART 3

GEOLOGY OF THE EAST EQUATORIAL PACIFIC

BY

GUSTAF ARRHENIUS

Contents

	Page
Chapter 3.1 Scope of the treatise	3
Chapter 3.2 Environmental subdivision of the East Equatorial Pacific	3
Chapter 3.3 Stratigraphy of the Late Cenozoic East Equatorial Pacific deposits	5
§ 3.3.1 East Eupelagic carbonate facies	5
.2 Present East Eupelagic clay and silica facies	8
.3 East Pacific Ridge	9
Chapter 3.4 Late Cenozoic evolution of the East Equatorial Pacific	10
§ 3.4.1 Tectonic evolution	10
.2 Climatic evolution as recorded in the East Eupelagic area	11

3.1 Scope of the treatise

The present part is intended as a summary of the stratigraphy and of the tectonic and climatic evolution of the East Pacific pelagic area. This summary is based on the facts, conclusions, and interpretations given in parts 1,2, and 4 of this volume. In a few cases, results have been anticipated from a later part of the volume, which is planned to deal with the distribution of iron and manganese in the deposits.

3.2 Environmental subdivision of the East Equatorial Pacific

The biofacies of the East Equatorial Pacific sediments is determined by the upwelling of deep water, rich in nutrients, and the resulting high productivity in the divergences of the Equatorial Current system (ch. 1.1, MURRAY and RENARD, 1891, ARRHENIUS, 1950). This causes a very marked latitudinal zonation of the composition of the sediment (ch. 1.1). With regard to this zonation the area might be subdivided in South Equatorial and North Equatorial carbonate facies, North Equatorial silica facies, and North Equatorial clay facies (fig. 3.0, at the end of part 3, 1, and 2). The boundary between the South and North Equatorial carbonate facies is formed by the Equatorial Divergence. The South Equatorial carbonate facies is represented only by core 62 (ch. 2.62). The average rate of biogenous accumulation is comparatively low in this facies (cf. fig. 3.3.1 and 1.1.6.1). The Equatorial Divergence represents an important subfacies. The apparent rate of biogenous production is here very high (ch. 2.61) and remains comparatively high also during ages of a lowered rate of circulation. In the North Equatorial carbonate facies the average rate of biogenous accumulation remains high below the Northern cell of the South Equatorial Current (0—5° N) and the Equatorial Convergence (5° N) (core 60 and 59) but is markedly decreased below the Equatorial Counter Current (core 58). The rate of calcium carbonate accumulation in the Equatorial carbonate facies is influenced by the rate of dissolution of calcium carbonate during settling and before burial

and in the East Pacific Ridge area presumably also by considerable postdepositional dissolution (ch. 1.1). With a rate of production of calcium carbonate decreasing northwards a boundary is reached where the rate of dissolution balances the rate of production of calcium carbonate and the rate of accumulation of calcium carbonate is thus = 0 (fig. 1.1.3.2). This boundary is called the present calcium carbonate compensation line and forms the northern border of the North Equatorial carbonate facies. The present compensation line appears to be located below the North Equatorial Divergence at long. 130° W. The rate of production in this divergence appears to be greatly surpassed by the corresponding rate in the Equatorial Divergence.

North of the present calcium carbonate compensation line follows the North Equatorial silica facies. The rate of production is still comparatively high, but not high enough to maintain accumulation of calcium carbonate. As a result biogenous silica is enriched on the bottom and siliceous clay or ooze accumulates. With further decreasing rate of biogenous production to the north the siliceous clay appears gradually to merge into clay, poor in organic remains. The corresponding facies is designated as North Equatorial clay facies. The boundary between this and the former facies is not well defined.

In addition to the differences caused by the above mentioned biofacies zonation, there are irregularities in the sedimentation, apparently caused by differences in bottom topography. With regard to this the East Equatorial Pacific has been divided into three topographical provinces, indicated in fig. 3.0; the East Pacific Ridge area, the East Eupelagic area and the Central Archipelagic area. The East Pacific Ridge rises over the 4 000-m curve, which has been taken as a boundary between the East Eupelagic area and Ridge area (contour according to SCHOTT, 1935, pl. 5). The boundary between the Central Archipelagic area and the East Eupelagic area has been arbitrarily drawn.

In the East Pacific Ridge area the topographical factor markedly influences the sedimentation process (ch. 2.38—2.48). Abnormally high and varying rates of minerogenous accumulation occur, redeposition appears to be frequent and in localities with irregular bottom topography slumping is indicated. The sediments are mostly rich in manganese and iron oxidates, which are believed largely to be of minerolytic origin (§ 1.12.6) and in some instances extensive diagenetical changes occur, which are believed to be caused by migrating solutions, whether juvenile or not is uncertain. The normal sedimentary record is not recognizable except in cores 39, 42, 45, and 46. A subordinate region is formed by the Galapagos area, which with regard to productivity belongs to the Equatorial Divergence subfacies. The concentration of oxidates is very low in this area, which may be due to the high content of organic matter in the sediment (reducing environment).

In the East Eupelagic area abnormalities in the sedimentation process appear to be restricted to local areas of abrasion and redeposition. The bottom profile is mostly undulating and indicates a greater topographical maturity than in the East Pacific Ridge area and in the Central Archipelagic area. Local volcanism occurs, at least in the North Eupelagic clay area, but appears to cause only local disturbances in the sedimentation. This is believed to be due to the fact that at great depths the eruptions take place as intrusions, without release of magmatic gases and therefore relatively quietly (s. ref. to RITTMANN in part 2). The rate of minerogenous accumulation was investigated in the Eupelagic carbonate facies from latitude 3° S to 8.5° N and was found to have been constant or subject to identical and simultaneous changes over the entire area during the last seven-hundred thousand years, whereas considerable

metachronous changes are recorded in the equivalent strata of the East Pacific Ridge area.

In the Central Archipelagic area topographical disturbances appear to affect the sedimentation, at least locally. Restricted areas with eupelagic sedimentation might occur within this area. The Central Archipelagic sediments are not included in the present treatise.

3.3 Stratigraphy of the Late Cenozoic East Equatorial Pacific deposits

3.3.1 East Eupelagic carbonate facies.

In the East Eupelagic carbonate facies (fig. 3.0, at the end of parts 1,2, and 3) the changes in the lithological and palaeontological composition of the deposit are largely determined by the changes in the biogenous component, whereas the minerogenous component appears to be homogenous in composition and constant with regard to rate of accumulation within the limits of the analytical error (ch. 1.2). Regional and temporary changes in the biogenous component appear to be connected to variations in the rate of production and in the rate of dissolution and disintegration of the biogenous matter during and after deposition (ch. 1.1). The changes in composition of the sediment with time appear to provide useful arguments for a stratigraphical subdivision of the sequences. To establish and check this subdivision, the spatial distribution of properties in the sediment, the relationships between the different properties, and the deviations from these relationships have been used. The stratigraphy of the East Eupelagic area forms the basis of the interpretation of the Late Cenozoic climatic evolution and ultimately of the absolute chronology of the Pleistocene (ch. 1.1, 1.2, and 3.4). The details of the relations and processes referred to above have been given in part 1 of this volume. The assumed geological evolution of the area is summarized in ch. 3.4.

The calcium carbonate concentration of the sediment is one of the properties which is subject to the most pronounced variations with time, and these variations have largely been used as a basis for the stratigraphical subdivision. The factors determining the calcium carbonate concentration have been treated in ch. 1.1, and the details of the vertical distribution of carbonate are shown in pl. 2.58—2.62. The gross features of the calcium carbonate curve have been used for the separation of time-rock units designated as stages, and the subordinate features for the identification of substages. Stages with a low content of calcium carbonate are designated with odd numbers, 1, 3, 5, etc. and stages characterized by a high content of carbonate with even numbers, 2, 4, 6, etc, the lower numbers corresponding to the younger stages. Substages are indicated by the number of the main stage and an additional number, which is even when the substage corresponds to an increased and odd when it corresponds to a decreased lime content. Thus substage 3.2 is the youngest (and only) substage with an increased carbonate content, found in stage 3 and substage 4.4 contains the penultimate (and oldest) subordinate carbonate maximum of stage 4. The top stage, corresponding to Postglacial, has a lowered carbonate content in the East Eupelagic facies and has the stage number 1. The top substage 1.1 appears to have a slightly decreased carbonate content and is overlying substage 1.2 and 1.3. The center of substage 1.3 is believed to correspond to the Postglacial Climatic Optimum. Further details of the sequence are given in ch. 1.1, in § 2.58.13—2.62.13 and in pl. 2.58—2.62.

The levels at which maximum rate of accumulation of calcium carbonate is attained in the even number substages and minimum rac in the odd number substages are designated as the substage centers. The intersections of these levels with a vertical north-south plane through the East Eupelagic area are indicated

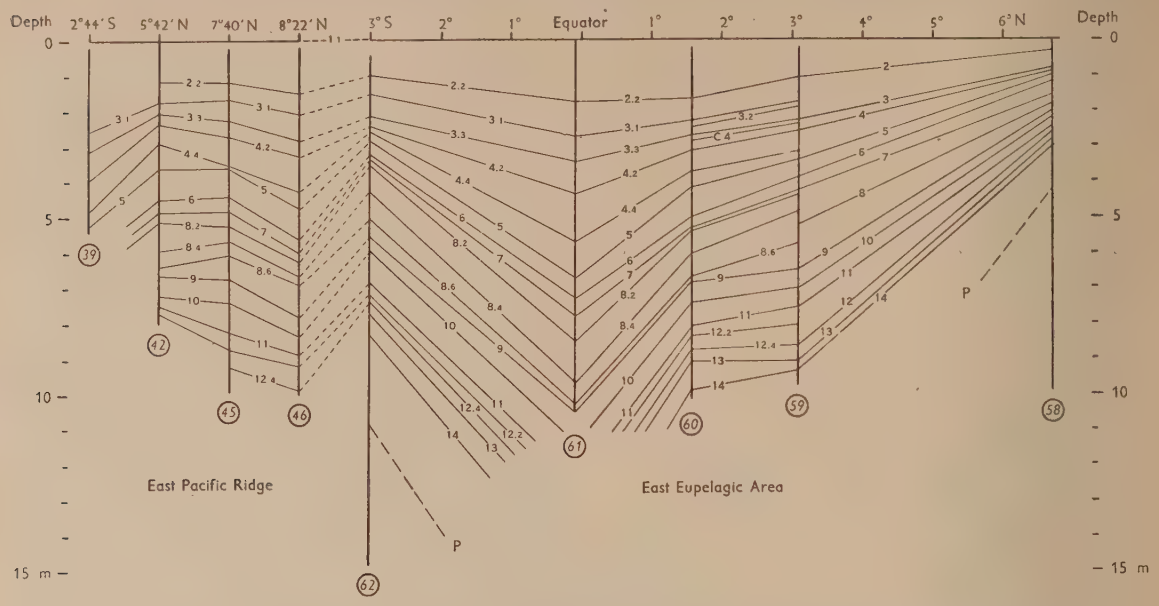

Fig. 3.3.1. Correlation of sediment cores in East Equatorial carbonate facies. The right part of the figure shows the section through the East Eupelagic carbonate area, and in the left part the correlatable cores from the East Pacific Ridge are put together. In this latter part of the diagram, the horizontal scale is arbitrary. In the East Eupelagic diagram the latitude is plotted on the x-axis. The vertical scale indicates the depth below the present sediment surface, which is idealized to a horizontal line. The sediment cores are indicated by vertical lines labelled with the core numbers. The grid lines correspond to the centers of substages and stages. A few substages have been omitted from the diagram (e. g. 4.3, 8.3, and 8.5) in order to increase the surveyability. P = suggested Pliocene-Pleistocene boundary.

in the right part of fig. 3.3.1. Difficulties in the direct identification of stages and substages may arise in regions where the differences in rac of carbonate are comparatively low, due to a perpetually high rac of biogenous matter, and further, close to the north carbonate facies border (fig. 3.0) where the rac of biogenous matter is low and the dissolution process has a still greater modifying influence on the amplitude of the changes in carbonate content than further away from the carbonate compensation line. Core 61 below the Equatorial Divergence is an example of the former effect and core 58 of the latter. In the Eupelagic facies, these difficulties have been overcome by using the variation of other properties than calcium carbonate (see below) as an aid at correlation and also by comparing the ΣTiO_2 of the sug gested levels. Without anticipation of the test of constancy of lutite accumulation it is obvious that if there are no indications of disturbances in the rate of lutite accumulation and if constancy of lutite accumulation has been proved in other parts of the sequence by the method indicated in ch. 1.1, it is most probable that untested isochronous levels in different cores have ΣTiO_2 which agree at least as far as the order of magnitude is concerned.

Subsequent to the correlation, the absolute age of the strata was determined by the radiocarbon-titanium method (ch. 1.2) in such cores where the rate of lutite accumulation was indicated to be constant.

Carbon and nitrogen could not be used for correlation purposes, due to the dominating influence of secondary changes on the concentration of these elements.

Phosphorus does not appear to be of direct use for the correlation in the Eupelagic carbonate facies, but is statistically a good indicator of the extent of postdepositional dissolution. After complementary research the phosphorus concentration may be used as a

basis for calculating the rate of calcium carbonate dissolution (§ 1.5.4).

The colour of the sediment (ch. 1.6) is subject to marked changes largely parallel to those caused by changes in the biogenous rac. As there are other factors also influencing the colour, this is not regarded as a reliable basis for correlation. Most of the factors determining the colour can in a much more accurate way be investigated separately. The colour and pattern of the sediment, however, gives valuable information with regard to the type and extent of reworking (§ 1.12.5). Postdepositional chemical redistribution often appears to be connected to typical colour changes.

The concentration of foraminifera is a valuable complement to the concentration of carbonate as an indicator of the environmental conditions. The abundance of coccoliths is indicated but not defined by the concentration ratio foraminifera/calcium carbonate (ch. 1.7). The laws governing the distribution of benthonic foraminifera appear to be relatively well defined and it is possible that the rac of benthonic foraminifera can be developed to a means of estimating quantitatively the rate of dissolution of calcium carbonate. The faunal percentage distribution of planktonic foraminiferal species is in the bathyal pelagic environment largely influenced by selective dissolution and disintegration. The fossil assemblages found can therefore not be assumed to give a detailed account of the composition of the original biocoenosis. For this reason great care must be taken at the paleoecological interpretation of the foraminiferal faunas. If due regard is taken to the possibilities of secondary changes, valuable information appears to be gained from the statistical distribution of planktonic species in this environment too. In many instances the information obtained is derived from the secondary changes observed rather than from the inferred original composition of the fauna.

Direct correlation of strata, exclusively based on the faunal composition, has not been attempted and is regarded as unreliable as far as the bathyal and abyssal environments of the oceans are concerned.

The concentration of diatoms appears to be a very useful property for stratigraphical and paleoecological purposes but suffers from the drawback that the quantitative work is expensive and takes much time. It is believed, however, that direct concentration measurements can be applied on a large scale after further development of the methods. Size distribution studies of *Coscinodiscus nodulifer* were of great value in the present work at the identification and subdivision of the Upper Pleistocene stages (ch. 1.9). The disappearance of the large size maximum in stage 4 takes place rapidly and the corresponding level C4 is therefore comparatively well defined stratigraphically (e. g. in cores 39, 59, and 60).

The rac of radiolaria varies as a rule in the same way as the rac of diatoms and that of $CaCO_3$ but the changes are less pronounced in the radiolarian rac than in the latter properties (ch. 1.8). This is believed to be due to the fact that the radiolaria are not concentrated to the surface layer of the ocean, where the most extensive ecological changes take place, when the rate of circulation is changed. The comparatively low sensitivity of the radiolaria to the ecological changes at the surface of the sea limit their value for Pleistocene correlation purposes.

For quantitative geochemical and geochronological studies on the basis of pelagic stratigraphy it is necessary to use salt-corrected analysis values and to know the volume weight relationships of the sediment. It is believed that the accuracy of the eupelagic titanium age determination can be considerably increased if determinations of the volume weight are carried out in each sample instead of calculating it from the salinity of the sediment.

A condition for quantitative studies of the kind referred to above is that no compaction

takes place at sampling. This requirement was fulfilled by the use of the Kullenberg piston corer.

A stratigraphical detail subdivison based on evolutionary changes was not attempted in the present material, and it appears questionable whether it can be successfully carried out, at least as far as Upper Pliocene and Pleistocene sequences are concerned. The boundary drawn between Pliocene and Pleistocene in cores 58 and 62 (§ 2.58.13 and 2.62.13) is thus based on climatological and paleoecological events and not on evolutionary changes. The boundary is defined by the marked decrease in percentage of *Sphaeroidinella dehiscens* (ch. 1.7), and by the marked circulation increase indicated by the rate of accumulation of calcium carbonate which is intensified in spite of the apparently increased rate of dissolution. The changes in rac of calcium carbonate at the transition from Pliocene to Pleistocene are best seen close to the facies boundary, i. e. they are much more obvious in core 58 than in core 62, where the change in composition of the sediment is not very marked.

3.3.2 Present East Eupelagic clay and silica facies.

In the present East Eupelagic clay facies there is no production mechanism in the sea, which like the divergences further to the south reacts in a sensitive way to the changes in trade wind intensity. The East Eupelagic silica facies represents the border of the equatorial high production area, where the amount of biogenous matter settling from the surface is comparatively high but not high enough to balance the calcium carbonate dissolution. It is assumed that both in this facies and in the East Eupelagic clay facies the varying amount of biogenous silica might account for the extensive Pleistocene circulation changes, although the record might be expected to be less marked in the latter facies type. Methodical development and additional cores are however required, before these changes can be accurately recorded. Owing to the low rate of accumulation (0.2—0.3 cm/1 000 years) the stratigraphical subdivision cannot be expected to be carried as far as in the East Eupelagic carbonate facies, as substages at least are homogenized by the standard reworking (§ 1.12.5). In the present material and with the analytical methods used, the Pleistocene, and presumably the Upper Pliocene, appear to form a homogenous lithological and stratigraphical unit (member P1, § 1.5.2, fig. 1.5.2.2), whereas considerable lithological changes are met with in the Late Tertiary strata underlying the member P1. These changes are reflected a. o. in the content of phosphorus and manganese in the sediment, and the phosphorus stratification has been used as a basis for a tentative stratigraphical subdivision. Details are given in § 1.5.2.

The existence of local areas of abrasion or non-deposition (ch. 2.53, 2.56, 2.57) in the North Clay area makes it possible to sample sequences of much greater age than the piston corer would allow if the sedimentation were continuous in all localities. Cores 53 and 57 represent outcrops of relatively old sediments, uncovered by abrasion or some other agent, and core 56 contains an unconformity apparently corresponding to several million years. The sequence of these cores (fig. 3.3.2) demonstrates that the East Eupelagic Late Cenozoic clay strata conformously overlie calcareous Tertiary sediments. The transition from calcareous deposits to clay and siliceous clay is thought to have been caused by an increased dissolution of calcium carbonate, ultimately dependent on a decrease of the temperature of the deep and bottom water of the ocean. The stratigraphical boundary (c) between calcareous sediments and clay would thus be identical with the calcium carbonate compensation surface (ch. 1.2). In the Pleistocene and Upper Pliocene this is assumed to be

an almost vertical plane, horizontally corrugated, with an approximately ENE—WSW strike in the East Eupelagic area and intersecting the Recent bottom plane along the present calcium carbonate compensation line (fig. 3.3.2). In the Tertiary the compensation surface appears to dip to the north and is thus believed to be older the further north it is found. The calcium carbonate content of the calcareous Tertiary strata is subject to marked changes, which might be used for correlation purposes.

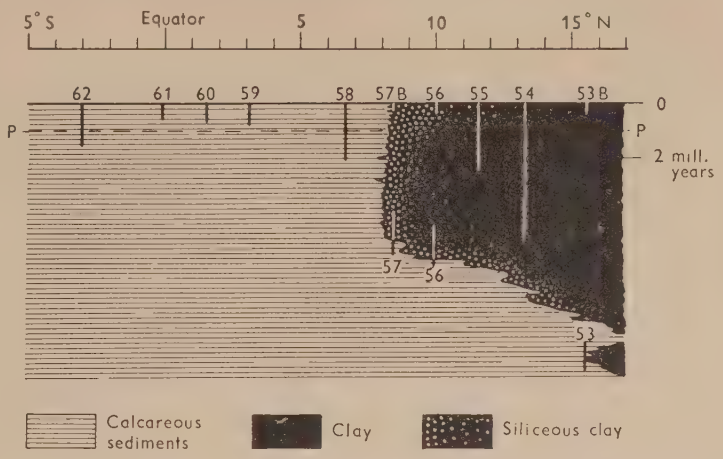

Fig. 3.3.2. Inferred intersection between the calcium carbonate compensation surface and a vertical north-south plane at appr. long. 130° W. The intersection with the compensation surface is indicated by the curve of the figure. Shaded surface indicates calcareous deposits. Black surface corresponds to clay and dotted surface to siliceous clay. P = Pliocene-Pleistocene boundary. The time scale extends only between 0 and 2 million years. The base of core 57 is believed to be Pre-Pliocene, and core 53 is possibly Miocene. The figure forms an interpretation of the information obtained from the sediment cores, which are indicated by vertical lines, labelled with the core numbers.

In the old sediments outcropping in the North Clay area, palaeontological dating methods can be applied. The Tertiary age of the strata above and below the calcareous Tertiary boundary in core 57 has thus been confirmed by palaeontological methods (ch. 2.57) and the Tertiary age of the calcareous core 53 has been made probable by such methods (ch. 2.53). The closer investigation of the foraminiferal faunas has not yet been completed and the results will be published elsewhere, presumably by F. Brotzen.

The strength of the sediment has proved to be of value as an indicator of surfaces of non-deposition and abrasion, which appear to be strongly indurated, and of unconformities, which appear to be characterized by marked discontinuities with regard to strength. The strength distribution provides, however, no definite proof for the existence of these stratigraphical features, as indurated strata, and laminae can be created also by secondary silicification (cf. § 2.41.12).

3.3.3 East Pacific Ridge.

Owing to the irregularities in the rate of accumulation, typical for the submarine ridge environment, and because of the extensive diagenetical changes of the sediment, the normal pelagic Pleistocene sequence can be recognized only in a few cores, viz. 39, 42, 45, and 46. In these cores the normal stratification is mostly well developed so that usually little doubt arises with regard to the identification of the main stages. As an example core 46, which in fig. 3.3.3 is correlated with core 60 in the East Eupelagic area 3 100 km to the west, might be taken. On the other hand the possibilities of checking the correlation of cores 42, 45, and 46 are poor, as the diatoms are strongly corroded and the rate of lutite accumulation varies widely. Only in core 39 are the siliceous fossils well preserved and the size distribution of *Coscinodiscus nodulifer* confirms the stratigraphical interpretation of the lithological changes. These are, however, in the case of core 39, markedly influenced by local disturbances and for this reason not even core 39 can be completely subdivided in substages. — The correlation of the East Pacific Ridge cores is shown to the left in fig. 3.3.1.

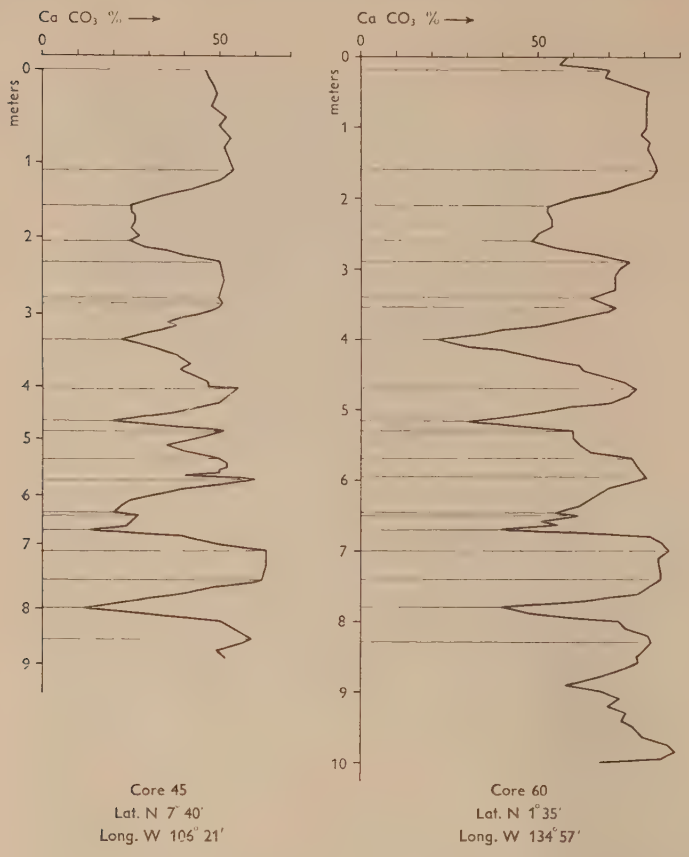

Fig. 3.3.3. Correlation of core 45 in the East Pacific Ridge area with core 60 in the East Eupelagic area, on the basis of carbonate stratification. In spite of the great distance between the two localities (appr. 3 200 km) and the variation in the rate of minerogenous accumulation on the East Pacific Ridge, the agreement between the sequences is regarded as fairly good.

3.4 Late Cenozoic evolution of the East Equatorial Pacific

3.4.1 Tectonic evolution.

In the East Pacific Ridge area it is difficult to interpret the sediment cores with regard to tectonic events as the stratigraphical record is often poor. Fine grained volcanic debris occurs in subordinate and varying amounts in many strata, but it is difficult to tell whether it is original or redeposited. The sequence in cores 45 and 46, which are correlated in detail, records (pl. 2.45 and 2.46) considerable local changes in the rate of minerogenous accumulation. It is assumed that differential vertical movements in the Ridge are the most probable reason for these changes, but it is impossible to study these quantitatively in the sequences in question. Generally it may be said that successful tectonic studies in unstable areas require a much more closely spaced system of cores than the present one.

From some of the sequences in the North clay area (cores 53, 56 and 57) it is evident that there has been a local interchange between deposition and erosion. It is regarded as most probable that this interchange was connected to local movements of the sea bottom, the elevation of an area causing transition from deposition to non-deposition or erosion, and vice versa. In the case of core 57 the erosional surface is situated on one of the shield-formed elevations which have been recorded in this area (cf. § 2.57.0). These may possibly be interpreted as the roofs of laccolithic intrusions in shallow depths below the sediment surface. Local volcanism in the North clay area is indicated by core 52 and by several samples from this area, described by Revelle (o. c.).

In the East Eupelagic carbonate area, tectonic stability appears to characterize at least the Pleistocene and apparently also the Upper Pliocene. In the vicinity of core 62 the bottom profile possibly indicates a series of fault scarps. To judge from the sedimentary record these are older than appr. 1.6 million years. This is also confirmed by the conditions found further to the South in the Central Archipelagic area, where irregular bottom with volcanic rocks is frequently found. The rock fragments sampled are deeply weathered, which is believed to indicate a great age.

3.4.2 Climatic evolution as recorded in the East Eupelagic area.

It is not yet known to what stage or stages the calcareous Tertiary sediments, which have been sampled in cores 53, 56, and 57 (fig. 3.3.2), belong. The facts that the calcareous Tertiary strata of core 57 are covered by several meters of siliceous clay with a Tertiary radiolarian fauna and that there are no marked differences between the Upper Pliocene and the Pleistocene faunas, suggest the probability, however, that the calcareous Tertiary deposits are older than Pliocene. The occurrence of calcareous deposits in core 53 at N 15.5° indicates that the calcium carbonate compensation line (ch. 1.1) was situated at least 800 km further to the North than at present. The main reason for this wide extension of calcareous deposits is believed to have been a comparatively high temperature and consequently a low aggressiveness of the deep and bottom water, which restricted the rate of dissolution of calcium carbonate. These conditions indicate a comparatively warm climate in high latitudes and a low rate of production of cold deep and bottom water in the polar areas. The faunal and lithological differences between the calcareous strata of cores 53 and 57 possibly indicate that the Late Cenozoic latitudinal zonation with regard to productivity in the sea, and thus the general pattern of the Equatorial Current System and of the Trade Wind System, was developed already in Pre-Pliocene time. During this time the concentration of phosphorus and halmyrogenous manganese in the sediment was considerably greater than in Late Pliocene and Pleistocene. This effect is believed to have been caused by an extensive transport of phosphorus and oxidates to the sea or by a decreased accumulation of lutite, or by both these effects.

Periodical changes in the climate towards cooler conditions are indicated by extensive variations in the concentration of calcium carbonate and phosphorus in the calcareous Tertiary strata (pl. 2.53 and 2.57). These climatic changes caused latitudinal fluctuations in the location of the calcium carbonate compensation line, which was at least in two instances depressed to the south close to core 53 at lat. 15.5° N (changes recorded in the member CT (3 + 2 y), pl. 2.53, col. $CaCO_3$). Finally, the compensation line was displaced to the south of core 53, (fig. 3.3.2) passed core 56 (lat. 10° N), and presumably at a later time moved slightly to the south of core 57 (lat. 8.5° N). The age relations of the boundary between calcareous sediments and clay in cores 53 (boundary not represented), 56, and 57 are not known and the time relations of the process of displacement of the compensation line are thus not quantitatively defined. The sequences of cores 53 and 57, however, indicate that there were alternating movements to the south and the north, the southward movements being more extensive, which resulted in a general displacement of the compensation line in this direction. In core 57 the calcium carbonate percentage drops from 60 to 0 % between 410 and 370 cm depth in the sediment. $\sum_{370}^{410} TiO_2 = 43$ mg/cm², which corresponds to 80 000 years if the rate of lutite accumulation was the same as in eupelagic Pleistocene deposits. The change from deposition of a sediment rich in lime to deposition of clay, practically free from carbonate, thus might under the above mentioned conditions be assumed to have taken place in appr. 80 000 years.

After passing core 57 in Pre-Pliocene time the compensation line appears to have remained between appr. 7 and 8° N at long. 130° W throughout Late Cenozoic time. In no case did it re-enter the region north of lat. 8° 25′ (core 57) during the time of deposition of the 3.7 m stratum of siliceous clay overlying the calcareous Tertiary strata in core 57 (presumably Late Pre-Pliocene and possibly Lower Pliocene), and at no instance during the last appr. 2.5 million years did it approach lat.

6° 44′ (core 58) very close from the north. The sequence of core 57 B (fig. 3.3.2 and pl. 2.57B) indicates that the carbonate area might have extended slightly north of lat. 8° 25′ during some of the low circulation ages of the Pleistocene period and definitely transgressed this parallel during the last of these ages (Postglacial — Recent) so that the present compensation line appears to be situated slightly to the north of 8° 25′ at long. 130° W.

Additional information regarding the fluctuations of the compensation line is gained from core 76,[1]) which is situated further to the West (long. 150° W). At this longitude the present compensation line appears to be situated at appr. 5° N. Core 76 is situated at 3° 45′ N and comprises Pleistocene and Upper Pliocene strata. The sequence demonstrates that the compensation line was slightly shifted southward to its present position in Late Pliocene or Early Pleistocene and that it took a position close to core 76 at least at two instances during the Pleistocene.

The exact form of the calcium carbonate compensation surface is not known, nor is its latitudinal minimum known in times older than the basal stratum of core 58 (appr. 2.5 million years) nor its latitudinal maximum in Lower Pliocene. The above mentioned facts with regard to the location of the compensation line after the Pre-Pliocene passage of core 57, however, indicate that probably no great deviations occurred in the time gaps which are at the present moment not covered by sedimentary records. A Late Cenozoic approximate equilibrium thus appears to have been established with regard to the location of the compensation line, which was apparently not depressed further to the south in spite of the intensification of the climatic conditions which led to the displacement of this line from 16° N to 8° N. The climatic change, which caused an increased production of cold deep and bottom water in the polar areas, seems also to have given rise to an increase of the atmospheric and oceanic circulation in low latitudes, resulting in an increased rate of upwelling and production in the Equatorial Divergences. The increased rate of production of skeletal structures consisting of calcium carbonate counteracted the increased rate of carbonate dissolution and prevented the depression of the calcium carbonate compensation line further south than to the North Equatorial Divergence.

The fact that the compensation line was subject only to small scale latitudinal movements during the Pleistocene proves that the path of the Equatorial Counter Current was not strongly deflected during the Ice Ages. This necessitates the assumption that the low latitude circulation increase was symmetrical with respect to the Northern and Southern Hemispheres which points to the probability that the Pleistocene climatic changes were isochronous in both hemispheres. It should be pointed out that this is not in agreement with the climatic theory of Milankovitch, which requires alternating deflections of the meteorological equator (and the Equatorial Counter Current) between 8.5° N and 8.5° S (Zeuner, 1945, p. 217—219).

The sequences obtained from the Upper Pliocene and Pleistocene in the Equatorial carbonate area (pl. 2.58—2.62) give a complete and detailed record of the accumulation changes during this period (§ 1.1.5—1.1.6) and the events recorded have been dated by means of the radiocarbon-titanium method (ch. 1.2). A schematic survey of the interpretation of the results is given in fig. 3.4.2. The ordinates in this graph are the titanium ages (core 60 used as a standard down to stage 14 and core 58 below this stage). The standard deviation of the age scale is caused mainly by the standard deviation of the radiocarbon determinations which is ± 6.3 % and there is thus fifty

[1]) This core belongs to the Central and West Pacific material, kindly placed at disposal by Professor Hans Pettersson for investigation.

percent probability that the scale should either be contracted so that the level which in the graph has an indicated age of one million years is instead 1 063 000 years old, or it should be expanded so that the level in question is given an age of 937 000 years. The possible age error arising from the stratigraphical correlation uncertainty and from methodical errors in the determination of ΣTiO_2 (ch. 1.2) is best seen from fig. 1.1.6.1. The abscissae of fig. 3.4.2 express the relative rate of low latitude atmospheric circulation in an arbitrary scale as inferred from the accumulation and dissolution phenomena and from the microfossil distribution, recorded in cores 58—62. It should be stressed that, at the present moment it is only possible to estimate qualitatively the relative amplitude of the circulation changes, and even the qualitative comparison is difficult as far as the Lower Pleistocene is concerned. It is regarded as definite that the maxima of the stages 4 and 2 are higher than all the others, that the last maximum in stage 4 (substage 4.2) is the highest of all, that the subordinate maximum in stage 3 (substage 3.2) is comparatively small, and that the Pliocene maxima are small compared with those of the Pleistocene. It is further regarded as very probable that the Lower Pleistocene maxima in stages 18, 16, 14, 12, and 10 are smaller than the maximum in stage 6, and the last two maxima in stage 8 (substages 8.4 and 8.2). Remaining details in the relative amplitudes of the circulation changes are inferred.

With regard to the correlation with the Pleistocene events in high latitudes the radiocarbon dating makes clear that stage 1 corresponds to Postglacial and that stage 2 falls in the Last Ice Age (Wisconsin).

Nothing is yet known with regard to the mechanism, which causes a high rate of low latitude atmospheric circulation during the even-number ages and a low rate during the odd number ages. It may be assumed that the increase of the circulation is global but it

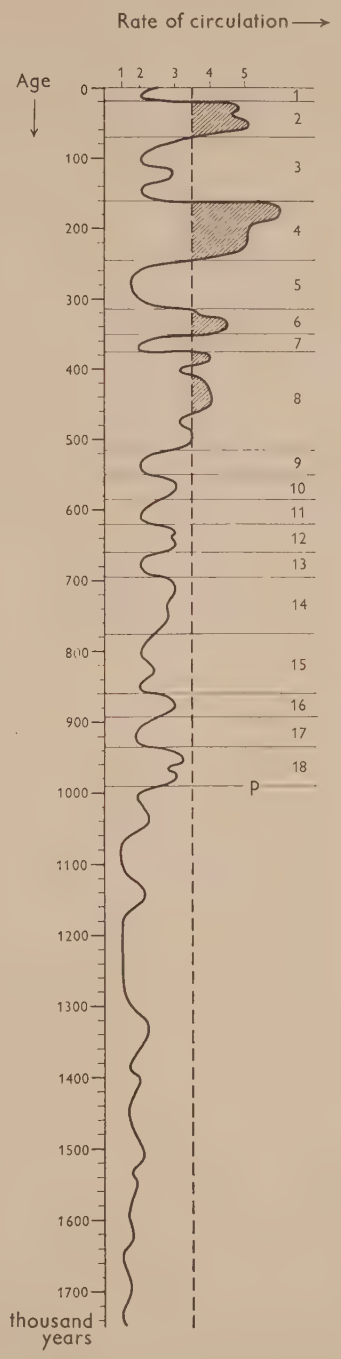

Fig. 3.4.2. Rate of low latitude atmospheric circulation as a function of time. The abscissa scale is arbitrary and the relative amplitudes of the circulation changes are inferred mainly from the quantitatively measured rate of accumulation of calcium carbonate, the qualitatively estimated rate of dissolution of calcium carbonate, and the quantitatively determined microfossil distribution. The dashed line corresponds to the inferred minimum rate of circulation occurring in connection with extensive glaciations. The Pleistocene main stages (1—18) are indicated and their approximate boundaries drawn in the diagram. P is the climatic Pliocene-Pleistocene boundary.

is also possible that there was a correspondingly decreased circulation in higher latitudes. Theoretically it might be assumed that the changes leading to an ice age of the Illinoian or Wisconsin type would at first cause an increase of the low latitude circulation, followed by a decrease connected to the culmination of the glacial climate, by a new increase during the climatic regression phase, and finally by a decrease corresponding to the interglacial age. Although this hypothesis appears improbable to the present author it might be taken in account and would imply that each of at least the last two ice ages would be corresponded by two even number stages in fig. 3.4.2. The stages 8, 7, and 6 would under such conditions correspond to the Penultimate Ice Age, stage 5 to the Last Interglacial Age and the stages 4, 3, and 2 to the Last Ice Age. This hypothesis appears improbable as it would imply that the Last Glaciation was more intense and had a longer duration than the Penultimate Glaciation, which is not in accordance with the evidence from the glaciated regions (cf. e. g. FLINT, o. c.).

It appears more probable and less far-fetched that each of the Equatorial Eupelagic main stages corresponds to an Ice Age. Stage 8 would thus be likely to correspond to the last Ice Age but four (Nebraskan), stage 7 to the Antepenultimate Interglacial (Aftonian), stage 6 to the Antepenultimate Ice Age (Kansan), stage 5 to the Penultimate Interglacial (Yarmouth), stage 4 to the Penultimate Ice Age (Illinoian), stage 3 with the obvious substage 3.2 to the Last Interglacial (Sangamon), and stage 2 to the entire Last Ice Age (Wisconsin). This interpretation implies that Lower Nebraskan has an age of 510 000 $\pm$ 32 000 years and that the last four glaciations occupy only the upper half of the Pleistocene period. Further there appear to have been at least five Pleistocene Pre-Nebraskan ages of such a strongly reinforced circulation that they might deserve to be called Ice Ages, although the record in glaciated areas might have been largely destroyed or disturbed (cf. FLINT, o. c., p. 277).

The climatic boundary between Pliocene and Pleistocene is indicated not only by a marked lithological change in the Equatorial Counter Current subfacies (core 58), but also by a sudden drop in the percentage of *Sphaeroidinella dehiscens* both in this subfacies and in the South Equatorial carbonate facies (core 62) (s. f. ch. 1.7). Within the Upper Pliocene several small increases occur in the rate of circulation, which because of the low rate of dissolution of calcium carbonate resulted in a comparatively high rate of accumulation of carbonate. The stratigraphical subdivision of this series has been postponed, as it is represented only in two cores, far apart and belonging to different facies types (cores 58 and 62).

A third possibility, which might be suggested in connection with the interpretation of the Late Cenozoic stratigraphy of the Equatorial Pacific sediments, is that the circulation changes recorded are in no way related to the interchange between glacial and interglacial ages. This is, however, regarded as most unlikely as it would depend on the assumption that extensive changes in trade wind intensity took place, poorly correlated with, or quite independent of the climatic evolution in high latitudes. Further, the apparent relation between Late Glacial and Postglacial continental evolution in high latitudes and in the oceanic facies of low latitudes would have to be explained as a mere coincidence. This third, hypothetical possibility is therefore rejected.

No attempts have been made to give a geophysical explanation of the low latitude circulation changes, as this is regarded as falling outside the competence of the present author and the scope of the present work. It might however be anticipated that increases in atmospheric circulation in the area investigated need not necessarily be caused by corresponding global increases of the atmo-

spheric circulation but could possibly be caused by longitudinal or latitudinal displacements of the high pressure centers in intermediate latitudes as has been indicated by NYBERG (contribution to vol. V, part 5, in preparation).

The Equatorial eupelagic record of the Late Cenozoic climatic evolution appears to be undistorted by the changes recorded and further to be detailed and chronologically well defined. On the continents and the continental shelves, climatic changes imply facies changes which render the quantitative study of the evolution difficult and often cause destruction of older parts of the record, whereas at the meteorological Equator in the Pacific Ocean the production mechanism has remained in its present position as far back in Cenozoic time as the evolution has been followed, recording the events by an increased or decreased speed. The analysis of the eupelagic stratigraphy of the Equatorial Pacific is therefore regarded as a most promising way to the quantitative understanding of the Late Cenozoic climatic changes. The approach to the problem made in the present work must be regarded as a trial, handicapped by the vagueness of the first attempt and the limitations of the roughly developed methods. It is believed that an improvement in methods of analysis will result in greater accuracy in the determination of the time and intensity factors and do full justice to the outstanding eupelagic Pacific material, to Dr. Börje Kullenberg's core sampling technique, and to the invaluable initiative of Professor Hans Pettersson.

References

ARRHENIUS, G. 1950. Late Cenozoic climatic changes as recorded by the Equatorial Current System. — Tellus *2*, p. 83—88 and p. 236.

FLINT, R. F. 1947. Glacial geology and the Pleistocene epoch. — N. Y. & Ld.

MURRAY, J. and RENARD, A. 1891. Deep sea deposits. — Rep. Sci. Res. Challenger.

REVELLE, R. 1944. Marine bottom samples collected in the Pacific Ocean by the Carnegie on its seventh cruise. — Carnegie Inst. Wash. Publ. 556.

SCHOTT, G. 1935. Geographie des Indischen und Stillen Ozeans. — Hamburg.

ZEUNER, F. E. 1945. The Pleistocene period. — Ray Soc. 130.

REPORTS OF THE SWEDISH DEEP-SEA EXPEDITION. VOL. V
SEDIMENT CORES FROM THE EAST PACIFIC

PART 4

METHODS USED AT THE STUDY OF THE SEDIMENT CORES

BY

GUSTAF ARRHENIUS

Contents

		Page
Chapter 4.1	Preparation of samples and storage of the material	3
§ 4.1.1	Treatment on board	3
.2	Unpacking	3
.3	Contamination	4
.4	Cutting	4
.5	Inspection, description and sampling	4
.6	Observed changes during storage	6
.7	Drying	6
.8	Pre-treatment of samples for chemical analysis	9
.9	Storage of the sampled cores	9
.10	Photography of stratigraphical features	9
4.2	Determination of shearing strength	9
4.3	Determination of hydrogen ion concentration	10
4.4	Determination of water content and amount of dissolved solids	10
4.5	Determination of carbonates and humus carbon	11
4.5.1	General statements	11
.2	Apparatus	11
.3	Procedure	11
.4	Accuracy	15
4.6	Determination of nitrogen	16
4.7	Determination of phosphorus	17
4.8	Determination of titanium	18
4.9	Quantitative microscopic analysis	19
4.9.1	General statements	19
.2	Treatment of samples	23
4.10	Numerical presentation of the results	24
	References	24

4.1 Preparation of samples and storage of the material

4.1.1 Treatment on board.

Immediately after collection on board, the sediment cores were cut into sections 70 cm long, superficially inspected, wrapped in water-proof acetate foil and grease-proof paper, inserted in aluminium tubes, molten in and sealed with paraffine and stored at a temperature of 4—10° C. A few short pieces were sealed in cardboard tubes.

The details of the treatment on board have been given elsewhere.

The East Pacific material was collected in September—October 1947 and opened in January—February 1949 and had thus been stored about sixteen months.

.2 Unpacking.

On unpacking, the aluminium tubes were cut through lengthwise with a circular saw along two generatrices and the tube halves removed from the paraffine covered parcel. The paraffine proved not always to have enclosed the sediment parcel entirely, but the ends appeared to have been perfectly sealed off and no evaporation from the sediment could be traced.

The three short core sections packed in cardboard tubes had all lost considerable amounts of water through evaporation.

The paraffine cover was removed together with the greaseproof paper. The glue tape with which this envelope had been sealed was in most cases attacked by moulds, especially *Aspergillus niger*. The inner envelope, consisting

of waterproof acetate foil, sealed with a solution of cellulose acetate proved, however, to be very resistant against moisture and could apparently not be used as a substrate by the moulds. This envelope was cleaned with a cloth moistened with 1 % formaldehyde before being cut open.

.3 Contamination.

In some cases there was local growth of moulds also on the surface of the sediment. The mycelium was in compact sediments, restricted to the outermost appr. 1 mm layer and could easily be trimmed off together with the asci. In a few core sections however, where the diagenesis had gone relatively far, the sediment was intersected by micro-fissures along which the mycelium had developed and was found although in small amounts only, in the interior of the samples. Growth of *Fusarium* was observed in two sections. In no case is the growth of moulds regarded to be of such importance as to influence the properties investigated.

In five instances (of two thousand) minute specimens of blattides have been found in the sediment, these being no doubt a contamination from the laboratories, where such animals were abundant. In seven instances remarkably well preserved specimens of acarides were found, and it is doubtful whether these were not derived from the supplies of fruit, which were transported through the laboratory to the cold storage. Theoretically such incidental contaminations with insects might cause sudden rises of the carbon and nitrogen content of the sediment. In practice such values can, however, be ruled out through control analyses.

.4 Cutting.

The core sections, freed from the envelope, were cut along their long axes in two equal halves. Plastic sediments were cut with a sharpened blade of stainless steel, $100 \times 5.5 \times 0.025$ cm stretched on a saw frame. This was supported in a wooden table with a slit. When lowered, the blade could enter a few mm. into this slit. The core section was placed over the slit, resting on acetate foil and held in position by two wooden strips, one on each side. Before cutting, the blade was moistened with water. After the knife had been lowered and the section thus had been cut into two halves, a second moistened blade was inserted in close contact with the first one. With this second blade sticking to its surface, one of the halves could now be removed, whereafter the blade was pulled off sideways. Through raising the bow with the cutting edge, the second half of the section was freed and taken away. The halves were handled and stored lying upon ¼ cut parts of the aluminium tubes and separated from these by water proof acetate foil.

Cutting with a blade could not be performed when the diagenesis of the deposit had gone so far that the sediment had lost its plasticity. In such cases the blade would break the core section into irregular pieces. For the cutting of such sections a steel wire 0.025 cm thick was used.

The blade leaves the cut surface of the sediment perfectly smooth without obscuring structural details through smearing. The wire gives the surface a lamellar structure, which can, however, easily be smoothed out with a knife, as the hardened sediments show no tendency of smearing.

.5 Inspection, description and sampling.

One of the two halves was photographed (§ 4.1.10) and stored untouched whereas the other was inspected and sampled. The inspection and description comprised checking of the annotations made on board, description of structure and colour and marking of the sample levels. Structural details of stratigraphical or petrographical interest were recorded by colour photography.

The colour of the sediment was determined on the freshly cut surface of the core sections

by comparison with the »Wilhelm Ostwald Farbtonleiter» (OSTWALD 1933).

The samples were cut out in slices, normally 1.5 cm thick or, in case of a high water content of the sediment, 2 cm thick. The outer 0.1—0.3 cm thick layer of material smeared over the surface of the core by the lining tubes was carefully trimmed off. In the cases where determination of water content was made, a small sample was separated for this purpose. The sample slice was then used for determinations of strength ch. (4.2) and finally dried (§ 4.1.7) and ground (§ 4.1.8).

In some cases the normal technique of cutting out plane parallel sample slices could not be used, viz. when the layers were bent by the friction against the lining tubes and when samples had to be prepared from structures such as digging holes, reaction yards etc. In such cases the samples were cut out with a thin knife.

The frequency of sampling was determined by the stratigraphical features of the sediment. As a general rule the maximum distance between two samples was 10 cm. This distance was used when the deposit appeared to be homogenous with regard to colour, strength and structure. When boundaries or transitions were found, samples were taken out close to these and on both sides. The average sample distance for the East Pacific cores thus amounted to 8.5 cm.

The samples were marked according to a code consisting of two groups of numbers, the first one indicating the core number and the second one the depth in cm of the upper surface of the sample slice below the top surface of the core. Thus 57—683 means a 1.5—2 cm thick sample with its upper surface located between the levels 682.6 and 683.5 cm in the core 57. Reworking of the sediment by mud eating bottom animals was found to be a characteristic feature in all normal pelagic deposits which made it meaningless to define the sample levels closer than related above, with the exception of a few special cases. For the same reason a decrease of the sample distances to less than 2—3 cm does not involve an increase of the stratigraphical accuracy in bathyal pelagic deposits brecciated by scavengers. The brecciation is not always perceptible to the naked eye when the breccia is single-coloured, but the presence of faecal pellets, mandibles of annelides, spines of echinoids, etc. often indicate its existence also in such cases. In those cases where sharp boundaries have been met with, these are mostly either of secondary origin and results of diagenesis such as concretionary zones or flint fronts or they are found in connection with beds deposited with an abnormally high rate of sedimentation.

Besides the normal sediment core raised with the piston corer there was sometimes taken from the same station a short column from the surface layer by means of an open tube corer. The sequences investigated indicate that using a long piston corer the upper centimeters of the column are lost, probably dragged down by the walls of the lining tubes and smeared out over the surface of the core (cf. PHLEGER, 1948, p. 1). This loss is conspicuous especially when the surface layer is poorly consolidated and semi-fluid. The use of a short coring device thus ensured the representation of the real top of the column. The short cores were stored on board in the original plastic lining tubes provided with stoppers in both ends and a stripe of filter paper impregnated with toluene attached to the upper stopper. The walls of the plastic tubes permitted slow evaporation of water, and most of the originally loose samples had been sufficiently consolidated after sixteen month's storage to permit cautious extraction of the column without flow or distortion. Two types of open tube core were used, one (A) with a core diameter of 4 cm, the other (B)[1]) with a diameter of 3.5 cm.

Samples still semifluid were left in the closed

[1]) described by PHLEGER (1951).

tubes and placed in dry atmosphere for a month before being extracted. Sampling of the small cores was carried out as described above, but a smaller average sample distance was chosen (appr. 4 cm). The sample numbers were given the additional index A or B.

.6 Observed changes during storage.

A feature often observed during the inspection on board was transverse irregular breaks in the cores, probably due to tensions during the coring operation. These breaks were mostly filled with the semi-fluid material smeared along the walls of the lining tubes and were always recorded in the log kept on board. Partly due to the thixotropy of the smearing material, partly to the diffusion of water within the core section during storage, the breaks were often difficult to recognize after storage without the aid of the annotations in the field log.

The inspection on board also comprised an estimation of the plasticity according to an arbitrary scale. The checking of these values after unpacking showed that parts of cores which were nearly semifluid on board had gained considerably in stiffness during storage. On stirring, however, the semifluid consistency was re-established, which indicates that the increased stability of the sediment is due to thixotropy rather than to loss of water through evaporation.

.7 Drying.

With regard to the forces which keep the moisture in the sediment, the water may conveniently be divided into gravitational water, capillary water, sorbed water, inclusion water and crystal water, although it may in many cases be difficult to differentiate clearly between two consecutive types. The course of the sorption-capillary condensation isotherms and isobars will be strongly influenced by the nature of the solid phase. Marine sediments have a complex composition but the constituents may be grouped together according to common features determining the moisture relationships.

Group 1. High temperature minerals, volcanic glass, and idiomorphic calcite. Crystal water is of no importance. Inclusions occur and in glasses solidified at great water depth and thus under high pressure, water also occurs in solid solution. The main part of the adsorbed water condenses as surface films up to a water vapour pressure of approximately 50 %, where the isotherms show an inflexion point (cf. NUTTING in REVELLE 1944, fig. 8.) The solid is now saturated with regard to adsorbed water and the increasing amount of vapour condensed when the vapour pressure is increased is a result of the depression of the vapour pressure at the concave menisci of the growing water wedges between the grains of the solid (PURI, 1925). If the vapour pressure is carried to saturation, this capillary condensation will go on with a decreasing rate until all the voids of the powder have been filled with water and the curvature of the menisci has disappeared. A surplus of water present in a sample may be classified as gravitational.

Group 2. Phillipsite. To the adsorption phenomenon is added the persorption of water molecules, whithin the molecular sized pores in the very open lattice, typical of the zeolites (MCBAIN, 1932. HEY, 1930. TISELIUS, 1936).

Group 3. Silica gel, organic matter, microcrystalline aggregates of secondary iron and manganese minerals. These, having a big internal surface, display the sorption properties of colloids. As in the case of zeolites, the capillary condensation (persorption) proceeds simultaneously with the adsorption, but the capillaries are formed by the intermicellar voids and not by channels determined by the lattice structure. There is thus a principal difference between the groups 2 and 3, whereas the deviating sorption properties of 1 and 3 are due to differences in particle size.

Group 4. Clay minerals, esp. montmorillonite. Sorption is to a high degree determined by the lattice structure and causes in the case of montmorillonite a pronounced dilatation along the c-axis. The sorbed water molecules are likely to have the structure of ice, the state of order being disturbed by salts present (FORSLIND, 1948). The sorption isotherms of monodisperse and salt free monomineralic clays show the discontinuities typical for definite hydrates (FORSLIND, ibidem). The sediment samples do not show this effect, which might be hidden by the polydispersity of the samples or prevented by their high content of salts.

Group 5. Sea salts. Isotherms and isobars form discontinuous curves, each step corresponding to the loss or gain of one or several molecules of crystal water. Samples containing soluble salts will not attain equilibrium at 100 % humidity due to the lowered vapor pressure of the salt solution. Marine sediment samples, if not freed from salts, therefore show deliquescence at high humidities. After drying over phosphorus pentoxide or concentrated sulfuric acid such samples are strongly hygroscopic, due to the very low vapour pressures of many of the systems: anhydrous salts $\leftrightharpoons$ primary hydrate.

It is not possible to find any point on the dehydration curves of the marine sediment samples where all essential water (cf. HILLEBRAND, 1919) is left in the solid and all non-essential water is driven off. The drying of the samples thus implies the removing of the gravitational water and of capillary, sorbed, included and crystal water to an extent which is in the last instance a matter of practical convenience.

For many analytical purposes it is considered advantageous to drive off as much water as possible through ignition of the sample. Irreversible destruction of clay minerals and of organic matter renders this method unsatisfactory in the present instance. Drying at 100°—120° C is often used in soil analysis but is less suitable when this is comprising also organic compounds which are partly destroyed when heated especially in reduced sediments. (ARRHENIUS, 1947, GRIPENBERG, 1934, MITSCHERLICH, 1923.) Drying at a temperature lower than about 35° C is therefore preferable in this case. Fairly small contents of moisture are obtained if the samples are put in equilibrium with a system with a low water vapour pressure such as $P_2O_5 + 3H_2O \leftrightharpoons 2H_3PO_4$, but it must be considered that by no means all the non-essential water is driven off by such a method. Drying of the samples to a very low vapour pressure equilibrium has a serious drawback viz. the resulting strong hygroscopicity of the material. The difficulties emanating herefrom are usually overcome through the use of weighing bottles and through the carrying out of the weighing operations immediately after drying. Such a treatment is not possible in the big series of analyses in question. The analysis material is compressed to pellets (§ 4.1.8) which do not sorb the moisture as rapidly as do the ground samples but rapidly enough to change their weight by several percent during the time elapsing between exposure to the air and weighing of the samples. An easier defined weight is attained if the sediment is dried to a vapour pressure as closely as possible corresponding to the average partial pressure of water vapour in the laboratory air (about 60 % of saturation at 20° C in this case) which can, if necessary, easily be regulated within a few percent. The relative smallness of the difference between the vapour pressure of the sorbed water in the samples and the partial pressure of water vapour in the air results in a very slow change of the equilibrium of the weight of the samples. The average increase of sorbed water amounts to 6.2 % of the sample weight at 0 % humidity if the relative humidity is increased from 0 to 60 % at 27° C, as calculated from Nutting's measurements (NUTTING, 1944). Nutting's maximum value for unfractionated samples is 7.4 % but according

to a personal communication from Dr. B. Kullenberg values higher than 10 % may be found (determination carried out at 20° C). It is, however, not known to what extent these values are influenced by the salt content of the samples, which tends to increase the sorption of water (see below).

As a hygrostat liquid a solution of H_2SO_4 in water with a vapour pressure at 20° C of 10.5 T was used. The air dried samples were put into equilibrium with the solution, partly in a vacuum desiccator, partly at atmospheric pressure in a thermostat with strong internal circulation maintained by a mechanical fan. Constant weight was attained within 24 hours in vacuum and within a few days in circulating air.

Weight—temperature relations of East Pacific sediments. If the present results should be compared with the results of other workers who adopted other drying methods, theoretically the isotherms and isobars ought to be known for all samples compared. The comparison is here carried out only with regard to the sorption conditions at a temperature of 105° C, which has frequently been used in sedimentological investigations e. g. by the Meteor Expedition and the Snellius Expedition. Sorption conditions for other temperatures may safely be interpolated as NUTTING (1944) has shown that the isobars for marine sediments are approximately linear between 50 and 105° C. The samples investigated were freed from sea salts through dialysis. Calcium carbonate oozes of high purity (92, 94 and 95 % $CaCO_3$) appeared to lose only very small amounts of water (0.22 0.31 and 0.03 %) when heated from 35 to 105° C, whereas the greatest losses were found in clayey samples. In tab. 4.1.7 are shown values of water loss between 35 and 105° C for salt-freed samples of carbonate-free East Pacific deep sea clays.

TABLE 4.1.7

Core no.	Loss of water %
48	3.3
51 upper	2.4
51 lower	2.5
54 upper	3.2
54 lower	3.2
55	2.0
56	4.5
Average	3.0

Only in the case of pure clays the water loss thus amounts to slightly more than the smallest error of analysis (compare descriptions of analytical methods 4.4—4.9), and the application of a correction for difference in water content is hardly necessary in any case when comparing the present results with those obtained from samples dried at 105° C. It must, however, be emphasized that a high content of sea salts in the sample markedly increases the water loss between 35° and 105°. Comparisons thus have to be based upon values corrected for salt content, for loss of water adsorbed by the salts and for loss of crystal water belonging to these. The analytical data given in this report are corrected for the salt content of the samples.

NUTTING'S (1944) values for dehydration of deep sea sediments resulting from heating are of the same order of magnitude as the values reported above, with exception of the Carnegie sample no. 31 (siliceous-calcareous red clay, South Pacific), which lost 13.2 % water between 50 and 100° C and displays an abnormal dehydration also at higher temperatures. It does not appear from Nutting's report whether the samples investigated were freed from sea salt or not.

Samples of the dehydration type Carnegie 31 have not been met with in the East Pacific cores investigated. It is desirable that the weight-temperature relations of the clays be investigated in each area of sedimentation. The relations found valid for the East Pacific cores should thus not automatically be applied to deposits from other areas until the frequency of samples of the type Carnegie 31 and the reasons for their abnormal behaviour have been revealed.

.8 Pre-treatment of samples for chemical analysis.

The dried sample was divided into two approximately equal parts, one of which was stored for microfossil investigation the other one ground for chemical analysis. For the grinding, a specially constructed agate roller mill according to O. ARRHENIUS (unpubl.) was used.

The agate rollers used were 5 cm long and 4 cm in diameter and could by means of adjustable springs be pressed against each other with a force of 100 kgf. The driving roller rotated with three times the speed of the other (10 and 30 rpm, resp.). The ground material was collected in a glass dish below the rollers. Each of the aggregates used consisted of two mills driven by a 250 W electric motor over a gear 1: 40. Rubber couplings were used to avoid vibrations.

The ground samples were kept in stoppered glass tubes. Previous to the analysis three pellets of each sample were pressed, one for the nitrogen-, one for the phosphorus- and one for the carbonate and humus carbon determination. The pellets were stored on wooden blocks each provided with a handle and holding two groups of five pellets each. The bottom plate of the press tool was rotatory and supplied with an excentric hole, an arrangement ensuring a rapid alternation from compression to expulsion.

The weighing of the pellets was carried out with an accuracy of $\pm$ 0.2 mg with a torsion balance (N. V. Vereenigde Draadfabrieken, Nijmegen) allowing an accuracy of $\pm$ 0.1 mg.

.9 Storage of the sampled cores.

The halves of the core sections were placed on water proof acetate foil on slices of the aluminium tubes, labelled and collected in boxes of galvanized iron plate. In order to keep the moisture content approximately constant and to prevent the growth of moulds and bacteria, each set of core halves was covered by a plate of porous wood pulp, impregnated with a 10 % solution of formaldehyde in water and separated from the sediment material by sheets of acetate foil. The boxes are kept at a temperature varying between +5° and +15° C and the contents are inspected every second year.

.10 Photography of stratigraphical features.

Ordinary photographs were taken from all core sections in the scale 1: 6.6. Indirect illumination was obtained from two 140 cm fluorescent tubes with a colour temperature of 3 200° K. The optical system used was a Goertz Doppel-Anastigmat, F = 18 cm with a blue filter from a three colour separation set. The emulsion, Kodak 0 250, was developed 21 minutes at 18° C with Kodak D-26 developer.

Colour photographs of details of special interest were taken in the scale 1: 1. Fluorescence tubes with a colour temperature of 6 000° K were used for illumination together with a weak correction filter (Kodak CC 33). The objective used was a Voigtländer Heliar 1: 4.5 F= 36 cm and the negative material Kodachrome Professional, Daylight, 9×12 cm, processed by the manufacturer.

4.2 Determination of shearing strength

As mentioned above, the deposits sampled by the piston corer cannot be regarded as mechanically undisturbed, the disturbances being due partly to the friction of the core against the walls of the lining tube and partly to the suction exercised by the rising piston at the beginning of the heaving in such cases when a maximum penetration of the corer was not attained. These effects are however counteracted by the thixotropy of the sediment, disturbed parts of which having reattained much of their original strength during the time elapsing between sampling and investigation.

The general brecciation of the deposit by bottom-living animals renders the material mechanically discontinuous and contributes to

the difficulties of interpreting smaller variations in strength and deviations of single measurements. However, the measurements of shearing strength give a general view of progress in the diagenesis and in some cases yield confirmative evidence of abrasion surfaces and unconformities.

The measurements were carried out with a falling cone apparatus according to the Geotechnical Committee of the Swedish State Railways (Statens Järnvägars Geotekniska Kommission 1922) modified by Wenner and Hedlund (Wenner 1950). A metal cone is suspended in a stand, the point touching the surface of the sediment sample. The cone is released by means of a trigger mechanism and falls freely into the sample. The depth of penetration is a function of the reciprocal of the sample's shearing strength which is calculated from the values of penetration and expressed in relative units indicating the theoretical weight of a cone having a top angle of 60° and penetrating 1 cm into the sample. Tables for the conversion of penetration depths to values of relative strength are given in the Report of the Committee cited above. Three parallel determinations were carried out on each sample. The results of the investigation are reported as the logarithms, multiplied by 100, of the relative values of strength referred to above.

4.3 Determination of hydrogen ion concentration

Approx. 100 mg of wet sediment were taken from the central part of the sample and mixed on a small watch glass with three drops of cresol red indicator, according to W. M. Clark (1928). After two minutes the colour of the supernatant liquid drop was compared with a colour standard against a brilliant white background. The error of reading was estimated at $\pm$ 0.05. Due to the presence of sea salts in the test solution there is a discrepancy between the pH values obtained by colorimetric determination and the corresponding results from electrometric measurements. The salt error of cresol red in sea water of varying salinity has been determined by Ramage and Miller (1925). The samples used for investigation contained 30—60 mg sea water which was diluted 3.3 to 1.7 times by the indicator, yielding a salinity of 10—20 $^0/_{00}$ of the sample solution. The corresponding correction range is, according to the above authors, —0.17 to —0.23. As the accuracy of the method used is limited to one tenth of a pH-unit, —0.2 has been applied as a standard salt correction.

4.4 Determination of water content and amount of dissolved solids

The amount of solids dissolved in the interstitial sea water is a property of the sediment, which is of importance as a correction factor for analytical results obtained through investigation of samples consisting of sediment together with the evaporation residue of the interstitial water and the water adsorbed by this evaporation residue. The amount of sea salts present in a sample is of interest also because it enables an estimation of the original water content of the sample. Direct gravimetrical determinations of water content were therefore carried out in a limited number of cases only, for the sake of comparison. Determinations of sea salts were based upon chlorinity titrations according to Mohr.

If the original chlorinity of the interstitial water was of the order of magnitude 19 $^0/_{00}$, the ratio dissolved solids/chlorine is equal to 1.83 (Sverdrup e. a., 1946). Experiments with sea salt obtained through evaporation of surface water from the East Equatorial Pacific indicated a loss of water of 7 % of the weight at 20° C and at a partial water vapor pressure of 10.5 T when the temperature was increased from 20° to 105° C. As the samples were dried under conditions corresponding to 10.5 T_{H_2O}

at 20° C (see § 4.1.7) they contain 0.7 mg of nonessential water for each 10 mg of salt. The total amount of matter not belonging to the sediment is thus obtained through multiplying the chlorinity value with the factor 1.96. In the present case the concentration of the titer solution was adjusted instead in such a manner that 1 ml of the solution corresponded to 1 mg salt + adsorbed water. About 100 mg of the sample were thus suspended in 50 ml water, 1 ml of 10 % potassium chromate solution was added and after one hour the solution was titrated with 0.0145 N $AgNO_3$.

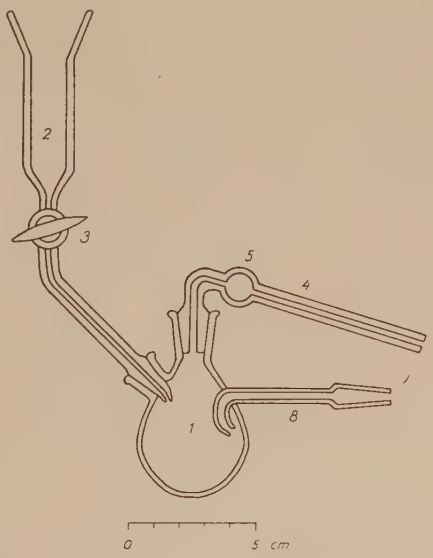

Fig. 4.5.1. Gas development flask (1—5) of apparatus shown in fig. 4.5.2.

4.5 Determination of carbonates and carbon

.1 General Statements. The method for the determination of carbonates and carbon in marine sediments was designed to answer to the following main requirements.

1) The accuracy of the analysis should be approximately ± 2 % of the carbonate value and in the case of the carbon determination correspond to approx. 0.08 % carbon.

2) The method must be practical in order to allow within a few years the analysis of the approx. 16 000 samples from the sediment cores of the Expedition. Gravimetric determination should therefore be avoided and carbonate and carbon should be determined in one sample in order to save weighing and handling operations.

The main features of the method designed to fullfill these demands are as follows: The sediment sample pellet is treated with dilute phosphoric acid, the developed carbon dioxide collected in a gasometer and determined volumetrically. The sample is then boiled with an oxydant, the carbon dioxide thus derived from organic compounds is collected and determined as above. For the oxidation of the organic compounds in the samples a 3.5 % solution of potassium iodate in concentrated sulfuric acid was used. The advantages of using iodate instead of dichromate have been indicated by Christensen, Williams and King (1937) and the iodate method has successfully been applied to soil analysis by Christensen, Simkins and Hiatt (1940).

The gasometer liquid, consisting of a 10 % solution of H_2SO_4 is saturated with $FeSO_4$, which serves as a reductant for the small amounts of chlorine formed by the decomposition of the sea salts present in the samples.

.2 Apparatus. The gas development apparatus consists of a gas development vessel, an electrical oven, a gasometer with level control, an air filter, an apparatus stand and a panel with terminal sets, switches and indicator lamps.

The gas development vessel (fig. 4.5.1 and 4.5.2) consists of a pearshaped 40 ml flask (1) with ground glass joints connected a) to a separatory funnel (2) with a stopcock (3); b) to an outlet capillary tube (4) with a bulb (5), plastic tubing (6) and a ground glass joint (7); and c) to the air inlet (8).

The cylindrical electric oven (9) (fig. 4.5.2 and 4.5.3) is covered by a lid of cemented asbestos with a central opening for the flask. The heating element consists of a steatite plate (10) with strips of mica (11) fastened with alundum cement. Between the mica strips

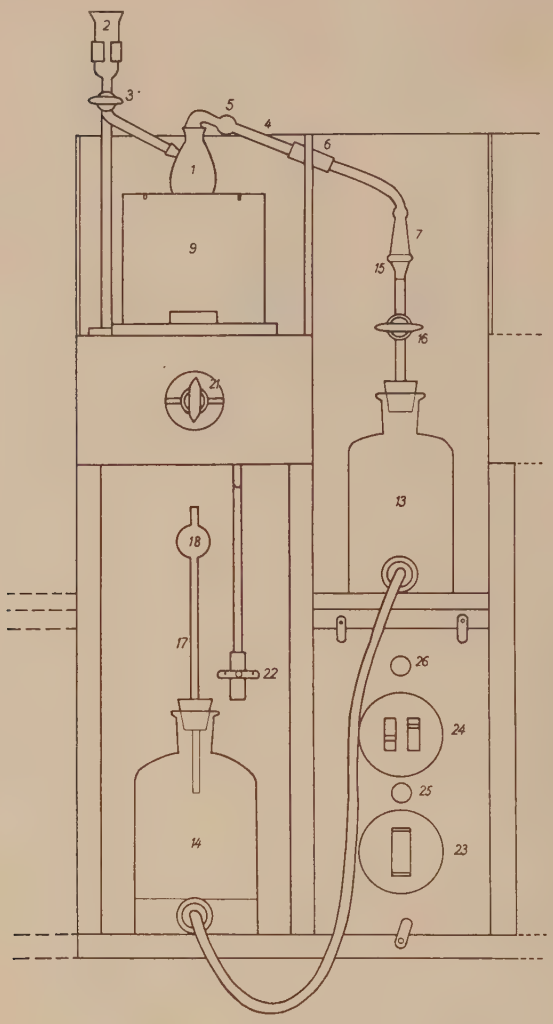

Fig. 4.5.2. Apparatus for development and collection of carbon dioxide from carbonates and organic carbon compounds.

a 0.2 mm Kanthal wire spiral (12) is attached. With 140 V the spiral attains a temperature of approx. 700°, and when 240 V is applied approx. 1 000° C. The wire spiral has a life time sufficient for 500—600 samples and can easily be replaced.

The gasometer consists of two tubulated bottles (13 and 14 fig. 4.5.2) with the volumes 0.75 and 1 l respectively. The smaller gas bottle is equipped with a ground glass joint (15) and a stopcock (16). A glass tube (17) provided with a reservoir bulb (18) is inserted through the stopper of the bigger reservoir bottle. Its lower end is adjusted so as to make the liquid rise into it when the level of the liquid in the gas bottle (13) approaches the bottom. The bottles are connected by means of a 1 m plastic tubing and filled with a 10 % solution of H_2SO_4 in water, saturated with $FeSO_4$. 20 gasometer sets were used simultaneously during the current work.

The air filter (F, fig. 4.5.4) consists of a glass tower, 30 cm high, 6 cm in diameter and filled with soda lime resting on glass wool. The air, freed from carbon dioxide, is distributed to the apparatuses by means of a tubing system shown in fig. 4.5.4. The air passage into the gas development vessel is controlled by means of a stopcock (21), the handle of which is protrudes through the front panel of the stand (fig. 4.5.2).

Water and sulfuric acid condensing in the air inlet tube behind the gas development vessel are trapped in a vertical tube branch, the mouth of which is closed by means of a pinchcock (22) located behind the bottle (14) in fig. 4.5.2. Ten sets of gas development apparatuses were used simultaneously.

The stand (fig. 4.5.2) is provided with three shelves, one for the oven (9), one for the reservoir bottle (14) and one for the gas bottle (13). Below the latter is put in the electrical control panel with main breaker (23), switch for 220 and 140 V (24), indicator lamp for 140 V (25) and for 240 V (26). Behind the panel are mounted the terminal set and a

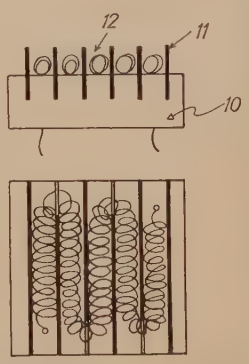

Fig. 4.5.3. Heating element of oven (9) in fig. 4.5.2.

buzzer indicating 240 V. The circuit diagram is shown in fig. 4.5.5.

Two types of carbon dioxide volumeters were compared with regard to their general qualities and their applicability for the special requirements of the case. Number one, the Lindberg volumetric carbon determinator was furnished by Fisher Scientific Co., Eimer & Amend Division, and number two, the Ströhlein volumetric carbon determinator, improved type 1947, by Ströhlein & Co, Düsseldorf. The Ströhlein device is shown in fig. 4.5.6 (by courtesy of the manufacturer). No drawing of the Lindberg device was available.

Both determinators use the same main principle. The gas mixture is collected in a graduated burette, levelled to the zero mark and thereafter twice pressed through (Ströhlein) or brought into intimate contact with (Lindberg) concentrated potassium hydroxide. Finally the volume of the carbon dioxide absorbed is directly read as percentage of carbon and corrected for temperature and pressure.

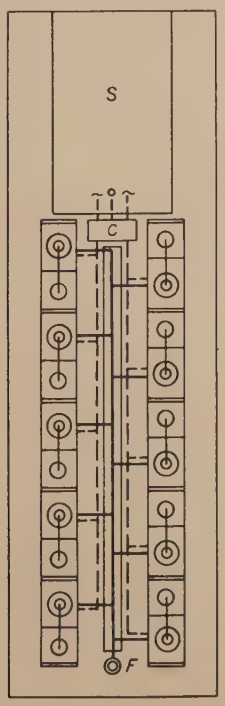

Fig. 4.5.4. Serial arrangement of apparatus shown in fig. 4.5.2. F, air filter, C, terminal set, S, shelf.

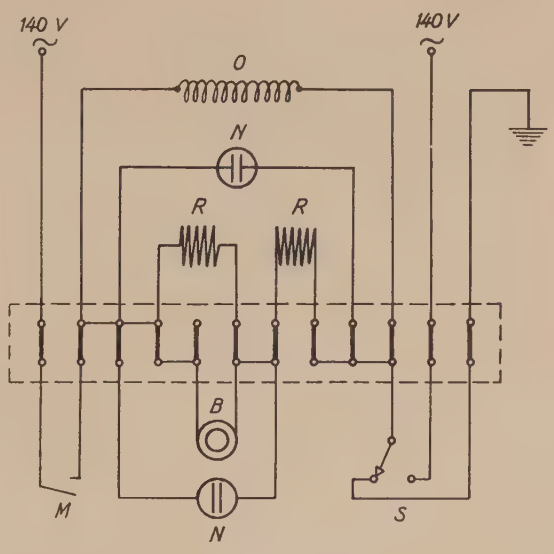

Fig. 4.5.5. Circuit diagram of apparatus shown in fig. 4.5.2. M, main breaker, N, neon lamp, B, buzzer, S, switch, R, resistance, 0, oven.

The volume of the ungraduated container of the gas burette is in the Lindberg case 505 ml against 300 ml in the original Ströhlein device. The bigger volume is preferable when the carbon determinator is used in connection with the gas development apparatus described above and was furnished on special request in case of the Ströhlein apparatus. The Lindberg burette has a standard graduated volume corresponding to 12.5 mg C which is very suitable for the determination of carbonates but somewhat big for the simultaneous determination of carbon in pelagic deep sea samples. Ströhlein burettes can be obtained in sizes corresponding to 2.5, 5.0, 15.0 and 45.0 mg C. A combination of two devices, one with a 2.5 and the other with a 15.0 mg burette is very useful for work of this kind, the carbonate measurements on calcium carbonate oozes being carried out with the bigger burette, the carbon contents as well as the small amounts of carbonates in clays being measured with the smaller one. The Lindberg graduation is etched on the burette whereas the Ströhlein burettes are provided with adjustable scales.

In the Lindberg apparatus the gas mixture

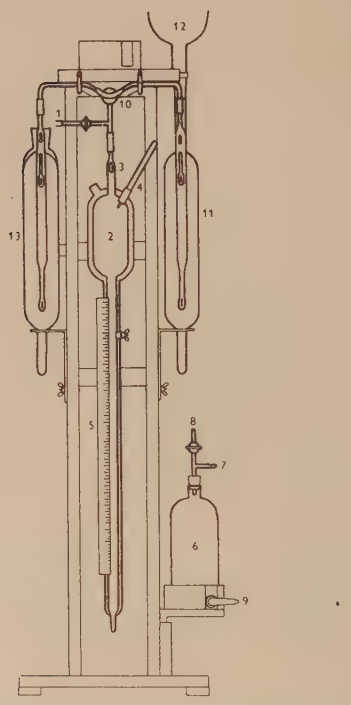

Fig. 4.5.6. The Ströhlein volumetric carbon determinator, improved type 1947. 1, gas inlet. 2, gas burette with automatical top vent (3), thermometer (4) and scale (5). At the lower end of the burette is attached a rubber hose, connected to the lower outlet (9) of the aspirator bottle 6. This is provided with a rubber pump, attached at 7 and is closed by means of the stopcock (8). By means of the three way stopcock (10) the gas is directed to the right absorption train (11) with reservoir (12), from the former into the left absorption train (13), and back to the burette (2).

is forced into the absorption vessel by means of lifting the aspirator bottle and brought back to the burette by lowering it, this procedure being repeated twice. In the Ströhlein case, the gas mixture is pumped through a first absorption train, from there automatically transferred to a second train and returned to the burette. This latter arrangement increases the speed of the process by 20 % or more.[1])

With regard to sturdiness and reliability of its component parts the Lindberg apparatus displayed during the current work several defects from which the Ströhlein model remained free and which could not be satisfactorily explained by the manufacturer. Finally, the Lindberg volumeter was abandoned.

The addition of a wetting agent such as lauryl alcohol sulfonate to the levelling solution proved to be a considerable improvement, as the draining of the liquid from the Pyrex glass walls of the burette took place more rapidly and completely and the capillarity of the graduated burette stem was considerably decreased.

For the present purpose the inlet tube of the burette was provided with a small SO_3-filter containing glass wool, moistened with 90 % H_2SO_4.

.3 Procedure. After washing, a few drops of water are left inside the gas development vessel which is placed on top of the oven (9) and connected to the air inlet joint behind this. The liquid level of the gas bottle (13) is raised to the top joint (15) of the bottle. The joints of the gas development vessel are moistened with concentrated phosphoric acid and the closed separatory funnel (2) connected with the flask. By means of an automatic pipette 3 ml, of a solution of 20 % H_3PO_4 and 2 % $FeSO_4$ are introduced into the funnel. The iron sulphate prevents oxidation of organic matter during the decomposition of the carbonates. (Clark and Ogg, 1942).

A small piece of pumice or carbonate free brick is introduced through the neck of the flask in order to prevent bumping during the later boiling of the sulfuric acid. The sample pellet (s. § 4.1.8) is now introduced the same way, the flask closed by means of the capillary tube (4) and the stopcock (16) of the gas bottle opened.

Upon opening the stopcock (3) of the separatory funnel the phosphoric acid solution is now sucked into the flask and reacts with the carbonates of the sample. When all the acid has entered the flask the stopcock is closed and 140 V applied to the oven. The temperature in the flask is raised to the boiling

[1]) The prices of the two carbon determinator types are in the approximate relation seven to one, the Ströhlein apparatus being the cheaper of the two.

point within 2—3 minutes and the boiling is carried on for 1—2 minutes in order to make sure that also dolomite is completely decomposed. The current is then switched off and the stopcock (21) opened to let in air. The falling gasometer liquid sucks into the bottle (13) the gas mixture from the vessel (1) and the tube (4) which are flushed with filtered air of appr. 14 times their own volume. When the liquid level has dropped to a position about 2 cm above the bottom of the bottle (13), the liquid rises into the tube (17), whereupon the draining is automatically stopped. The stopcocks (16) and (21) are now closed, the gasometer set is brought to the volumeter and replaced by a new one. 5 ml, of a 4 % solution of KIO_3 in conc. H_2SO_4 are introduced into the funnel by means of another automatic pipette, the solution drained into the flask as indicated above and 240 V applied. Within 3—4 minutes the temperature is raised to the boiling point (approx. 200° C), after which the voltage is decreased to 140 V and the heating maintained for 45 minutes. Samples of some siliceous clays showed a tendency to bump in spite of the presence of brick pieces. The addition of approx. 0.1 g calcium phosphate P. A. effectively prevented this disturbance. The boiling flask and the tubing system are finally flushed with air as described above and the gasometer brought over to the volumeter for determination of the content of carbon dioxide.

The gas bottle (13) is connected to the ground glass joint of the inlet tubing of the burette and the gas mixture is transferred to this. The gas volume of the bottle has been adjusted to 500 ml, which is slightly smaller than the total volume of the gas burette (530 ml). The remaining 30 ml space of the burette is filled by carbon dioxide freed air sucked in through an ascarite column, thus flushing into the burette the traces of CO_2 remaining in the capillary inlet tubing.

After the liquid of the burette has automatically attained the zero level, the gas mixture is twice pressed into the absorption vessel, if the Lindberg apparatus is used; or in the Ströhlein apparatus, pumped into the first absorption vessel, from where it is forced by the accumulated pressure through the second absorption train, and finally returned to the burette. 1 minute was allowed for the draining of the burette walls after the carbon dioxide mixture had been collected from the gasometer bottle and again after the inert gas rest had been sucked back from the absorption train. The primary result was directly read on the burette, which is graduated in mass of carbon, the distance between the marks (approx. 3.5 mm) corresponding to 0.10 mg C or 0.93 mg $CaCO_3$. — The volume reading as well as the temperature, pressure and sample weight were tabulated and the figures transferred to punched cards whenever a thousand samples had been analysed. The final results expressed as $CaCO_3 \cdot 10^3$ and $C \cdot 10^4$ were calculated from the punched cards together with the results from the other analysis groups by means of a Hollerith multiplier.

4. Accuracy. The maximum sample weight is limited by the space of the graduated burette stem. This volume corresponds in the Lindberg burette to 12.5 mg carbon in the form of carbon dioxide at 18° C 760 T or to 104 mg of pure calcium carbonate or to 110 mg of a sample containing 95 % $CaCO_3$, which is the maximum value as far as salt containing samples are concerned. The accuracy of reading is approx. 1 mm. An error of reading of 1.5 mm corresponds to approx. 0.4 mg $CaCO_3$ and thus to less than 0.5 % of the maximum content of calcium carbonate. If 0.5 % C is taken as the average content of humus carbon in carbonate-rich deep-sea sediments the reading error for carbon amounts to less than 10 %.

At the preparation of sample pellets, the approximate calcium carbonate content of the sample groups was estimated and the pellet weights adjusted to 100—110 mg for samples

very rich in carbonate, 120—140 mg for rich samples, 150—200 for samples of an average carbonate content, 200—400 for samples of samples with low content and 450—500 for samples assumed to be practically free from carbonates. The weight was limited by the range of the torsion balance used. The pellet weights were determined with an accuracy of ± 0.2 mg.

To the reading error is added the experimental error, the final accuracy of the $CaCO_3$ determination being approx. ± 2 % at a content of 95 % $CaCO_3$. The gliding weight scale results in an increasing absolute accuracy with decreasing carbonate content and in a slowly decreasing accuracy if expressed as a fraction of the carbonate concentration. The accuracy of the carbonate analysis is thus approx. ± 2 % of the calcium carbonate value at the highest percentages, ± 4 % of the calcium carbonate value at approx. 20 % $CaCO_3$ and ± 0.4 % absolute in deposits poor in carbonates.

For humus carbon the standard deviation corresponds to approx. ± 0.04 % C or ± 8 % of the carbon content of pelagic calcium carbonate oozes. The carbon content of the pelagic clays investigated is approx. five times smaller (0.1 %) than that of the carbonate oozes, but as the pellets can be made five times bigger the error expressed as percentage of the analysis value on the average remains constant as far as normal pelagic deposits are concerned. In terrigenous muds and oozes comparatively rich in organic matter the relative carbon error becomes considerably smaller.

4.6 Determination of nitrogen

The determination of nitrogen was carried out by means of a modification of the micro-Kjeldahl method described by Pregl—Grant (1945).

As micro digestion flasks Pyrex test tubes 18 × 1.7 cm, were used and as a digestion stand a sand bath 60 × 23 cm covered by a plate perforated by 1.8 cm holes arranged in six rows, each row holding 20 test tubes. The sand bath was heated by an electrical element consisting of approx. 20 m 0.075 cm Kanthal wire wound on the upper side of a cemented asbestos plate resting on the bottom of the sand bath.

A double set of the distilling apparatus of Parnas and Wagner (1938) was used. The inlet funnel was sealed to the apparatus instead of using a rubber tubing connection, and the funnel was closed by means of a long shafted ground glass stopper. The sample was removed from the distilling apparatus by means of a motor pump instead of the original low pressure trap. The sample pellets had to be treated in different ways, depending upon their content of carbonates. Clayey pellets if immersed in strong sulfuric acid do not decay as do calcareous samples but keep their shape and become indurated during the heating process. Clayey pellets were therefore introduced into the test tubes before the acid and allowed a minute or two to absorb the one or two drops of distilled water which had remained in the tubes after washing. By means of an automatic pipette 3 ml of a 67 % solution of H_2SO_4 containing 5 g H_2SeO_3 and 4 g $CuSO_4 \cdot 5\,H_2O$ per liter were added after which the sample was put on the sand bath for heating. In the case of calcareous samples the acid was introduced into the test tube before the pellet.

As in Swedish glacial clay (G. Arrhenius 1947), it appeared that the nitrogen compounds of the organic matter are hydrolyzed only with great difficulty, the samples normally requiring 24—48 hours heating at 170° C before the recovery of the nitrogen is practically complete. During the first six hours of heating 60—80 % of the nitrogen is converted to ammonium sulphate. If the samples contain 1 % or more of humus carbon, care is necessary during the first hour of heating as the formation of CO_2 easily makes the sample boil over or causes the suspension

to rise along the wall of the test tube and thus escape from the zone of heating. Total destruction of the organic matter in the sample is indicated by disappearance of the brown colour in the supernatant liquid. After cooling, the sample was transferred to the distilling apparatus and the test tube washed three times with a total amount of about 10 ml distilled water. 10 ml of a solution of 570 g NaOH/l were introduced into the apparatus, the funnel was washed with approx. 1 ml water, then closed and the steam generator connected. If the concentration of acid in the sample is properly adjusted, the temperature rises to near the boiling point when the strong sodium hydroxide is mixed with the sample by the water vapour current; and the process of distillation begins after a few seconds.

For the titration of the ammonia the method of Ma and Zuazaga (PREGL 1945) was applied. The hydrochloric acid used for the titration was made 0.00714 N, 1 ml of this solution corresponding to 0.1 mg nitrogen.

Due to the pH change when the boric acid solution becomes diluted the distillation has to be carried on to a known volume. The amount of hydrochloric acid required to restore in the distillate the pink shade of the original boric acid solution depends partly on the amount of ammonia distilled over and partly on the change of pH through dilution of the boric acid. During the process 5 ml 1 N boric acid are diluted to 20 ml which increases the pH from 3.94 to 4.25. By a series of blank titrations the corresponding titration correction was found to be $= -0.15$ ml.

The experimental error amounts to $\pm$ 0.005 mg N (ARRHENIUS 1947, p. 59) corresponding to approx. $\pm$ 2.5 % of the average nitrogen content of deep sea deposits if this is assumed to be 0.5 mg/g and the average pellet weight used is 0.4 g. The analytical results are calculated on salt free sediment by means of the readings recorded in the punched cards and $N \cdot 10^5$ is used as unit.

4.7 Determination of phosphorus

The method used is based upon the colorimetrical determination of the blue ammonium phosphomolybdate complex with sulphite and hydroquinone used as reductants (BELL and DOISY, 1920). The method has been modified by O. ARRHENIUS (1929), who also investigated the factors influencing the stability and intensity of the colour. The method of O. Arrhenius has been adapted for the present purpose although altered in some details with regard to the special properties of the material investigated.

Approx. 100 mg was chosen as pellet weight for clayey samples, 450—500 mg for samples rich in carbonates. The pellets were heated with 5 ml conc. H_2SO_4 in Pyrex test tubes in the same way as the nitrogen samples, the same precautions in connection with the dispersion of the pellets being taken as in the case of the nitrogen analysis. After 12 hours' heating each sample was cooled and transferred to a 100 ml-volumetric flask which was then filled up to the mark with water. The solids of the suspension were allowed to settle for several hours and 25 ml of the clear solution were transferred to another 100-ml volumetric flask, 10 ml of solution A added from a double automatic pipette, 2 ml of solution B by means of an all-glass syringe and finally the flask was filled up to 100 ml with water.

Solution A is prepared by dissolving 250 g ammonium molybdate in 5 l water, adding 1.75 l H_2SO_4 and diluting to 10 l.

Solution B contains 250 g sodium sulphite cryst. and 5 g hydroquinone in 2 l water. The solution should be kept in a stoppered brown glass bottle and renewed each month. In addition to each daily series of 100 sample flasks a standard series was prepared; each 100-ml flask of this contained from 0 to 12 ml standard solution, 1.5 ml 83 % sulfuric acid, 10 ml of solution A, 2 ml of B and water to 100 ml. The standard solution contains 95.8

mg/l KH_2PO_4 (Sørensen), each ml corresponding to 0.005 mg P_2O_5. The sample flasks were put in a thermostat together with the standard flasks and kept at 50—60° C for 14 hours, cooled to room temperature and compared with the standard flasks. The accuracy corresponds to approx. 0.4 of the difference between two members of the standard series. The standard flasks contain respectively 0 25 50 75 100 125 150 200 250 300 350 400 450 500 and 600 γ P_2O_5. The weights of the sample pellets were adjusted according to the experiences gained about the carbonate content of the sample and about the phosphorus content in clay residues of different deposit types in such a manner that the content of the sample flasks generally corresponded to appr. 125 γ P_2O_5. Thus the error of reading, which in this case determines the total error, amounts to 0.4 (150—125) = 10 γ P_2O_5, that is to $\pm$ 4 % of the analysis value.

The readings and sample weights were recorded on punched cards and the concentrations computed automatically. The concentration values have been expressed in the unit 10^{-4}.

4.8 Determination of titanium

The aim of the present method was to change the titanium contained in deep sea sediments into soluble compounds without previous separation of the sesquioxides. For this purpose the sample might be directly fused with a suitable flux e. g. an alkali pyrosulfate and the melt subsequently leached. But the calcium sulphate and especially the silica of the sample render the cooled melt very hard and compact, difficult to crush or leach. This difficulty was overcome by mixing sample and flux powders intimately with graphite which is slowly oxidized during the fusion, forming bubbles of carbon dioxide. The melt is thus transformed into a well stirred foam which after cooling easily decomposes in the leaching solution.

Another requirement of the present investigation was that the volume of the dilute sulfuric acid used for the leaching of the melt should be well defined and not changed during one or two days' standing in the open beakers used as fusion vessels. The concentration of the acid was therefore adjusted so as to create an equilibrium of water vapour pressure between the system melt — acid and the laboratory air.

After dissolution, the amount of titanium was determined colorimetrically according to the well known method of Weller.

The amount of each sample taken for analysis varied between 50 and 1 000 mg, the weight being chosen so as to yield 0.1—0.7 mg TiO_2. With some practice the weight to be used could be estimated in each case from the known calcium carbonate content of the sample. The powdered sediment was thoroughly mixed with 8 g potassium bisulphate and a volume measure of pure graphite corresponding to approx. 0.7 g. The bottom of a 30 ml Pyrex glass beaker was covered with a 1 mm layer of graphite and the mixture sample — flux — graphite cautiously poured on top.

Twenty beakers were placed in a muffle furnace and the temperature was slowly raised to attain 500° C after 3 hours. This temperature was maintained for one hour, after which the samples were cooled and 10 ml 43 vol % H_2SO_4 added. The solution thus formed is stable at 18° C and 65 % humidity. After one day's leaching, the main part of the solution was transferred to a 100 ml bottle, the solid residue crushed with an agate pestle and washed into the bottle with 39.8 ml water from an automatic pipette. Subsequently the closed bottle was rotated for 12 hours in a shaking machine, the suspension filtered, and 0.2 ml 30 % hydrogen peroxide added from a glass syringe. The extinction of the coloured solution was evaluated by means of a Zeiss Pulfrich Stufenphotometer, specially furnished with 10 cm cylinder cuvettes. These were fixed to the

photometer stand and fitted with bottom outlet tubes with stopcocks, top inlet tubes with funnels, and a top outlet for air thus allowing rapid draining, washing and filling. The end-plates of the cuvettes were attached to the cylinders by means of half-polymerized methyl metacrylate which was subsequently polymerized. The comparator solutions were prepared in the same way as the sample solutions but without addition of hydrogen peroxide. The error of reading amounts to $\pm$ 1.5 %. The results expressed as $TiO_2 \cdot 10^4$ are averaged from three or more parallel measurements and corrected for the salt content of the sample.

4.9 Quantitative microscopic analysis

4.9.1 General statements.

With regard to the aims of the investigation and the positive experience gained by the first surveying work, all microscopic investigations of the fractions down to 150 μ, and as far as possible also of the fraction below this limit, were carried out on an accurately weighed amount of the dried sediment and corrected for the content of salt and salt-sorbed water of the sample (4.4). In the present report the results are expressed as number per gram of air dry and salt free sediment (= concentration). These concentration values have in some special cases been recalculated on a volume basis or time-interval basis. The concentrations of different species or species groups of pelagic foraminifera have been used for recalculating the corresponding faunal composition on a percentage basis. Concentrations of benthonic foraminifera are given separately from concentrations of plankton.

The material investigated was divided into three size groups, $> 500\,\mu$, $150-500\,\mu$, and $< 150\,\mu$. These upper and lower size limits were originally suggested by Brotzen and proved to be very useful with regard to the distribution of different fossil groups within these size fractions.

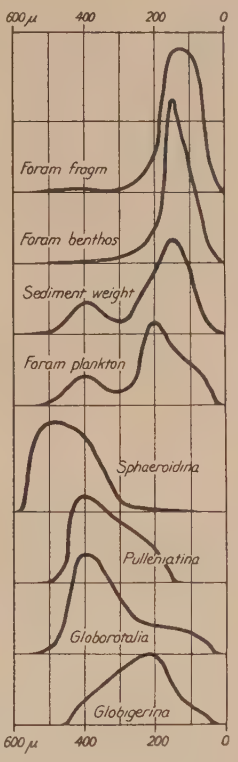

Fig. 4.9.1. Grain size distribution of foraminiferal constituents and total sediment, except clay fraction. Sample from core 62, 781 cm.

This distribution is exemplified by the sample 62—781 in fig 4.9.1 to 4.9.3. From fig. 4.9.1 and 4.9.2 it appears that if all quantitatively important fossil groups should be represented in their correct proportions, the lower size limit

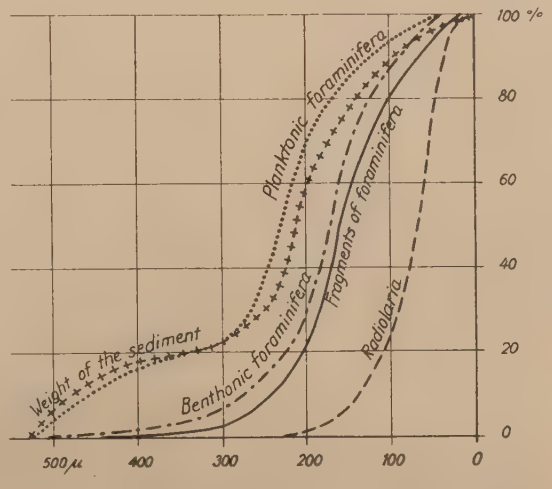

Fig. 4.9.2. Cumulative representation of the grain size distribution of the constituents shown in fig. 4.9.1 and 4.9.5.

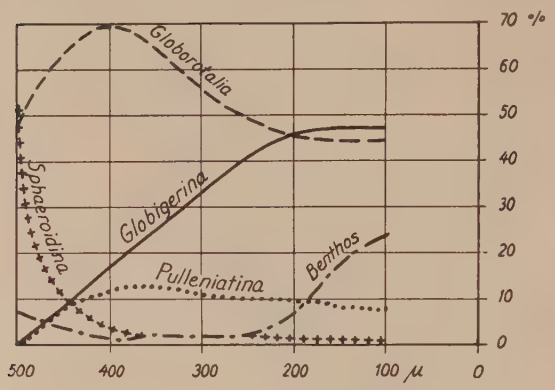

Fig. 4.9.3. Change of apparent faunal composition of sample 62—781 with changing lower limit of the grain size.

should not exceed 25 μ. This, however implies great practical difficulties, and most workers therefore have preferred to use much higher minimum limits. The influence of the particle size upon the results appears not to have been generally realized, and many workers do not even state which lower limit they have chosen. The first critical work published in this field as far as is known to the present author is a paper by Brotzen (1936). Similar points of view were recently stressed by Said (1950).

In common practice 200 μ has often been chosen as a lower size limit for quantitative investigation of foraminifera (e. g. Schott 1935).

From fig. 4.9.3 it appears that the percentage composition of the pelagic foraminiferal fauna is only slightly changed if sample fractions of less than 200 μ grain size are included in the investigation, but that the real percentage of benthos is poorly reflected by the faunal elements larger than 200 μ. This has earlier given rise to the widely accepted but erroneous conception that benthonic foraminifera are scarce in pelagic deep sea deposits. In the present material, concentrations of benthonic foraminifera as high as or higher than corresponding concentrations of pelagic specimens are not rare. Qualitative observations pointing in the same direction were made by Revelle (1944). Besides, lowering the minimum size limit to below 200 μ increases considerably the significance of the estimation of concentrations of planktonic foraminifera, foraminiferal fragments, radiolaria, fish teeth, mineral grains and other findings. Below 150 μ the technical difficulties of the sieving process increase rapidly, so that 150 μ may be regarded practically as a lower limit for sieving material which does not consist of massive and approximately isometrical grains. Elutriation technique can not be applied to the material in question as there are large discrepancies between the hydraulic values and the dimensions of the grains.

Foraminifera. The principal aim of the investigation of foraminifera was to elucidate quantitatively the geognostic significance of production of individuals, deposition of shells and secondary changes of the deposit. For this purpose the subdivision and study of separate taxonomic groups was of subordinate importance, the main interest being directed to absolute concentrations of shells, the relations of these concentrations to other properties of the deposit and the proportions between planktonic and benthonic faunal elements. Simultaneously with these investigations a taxonomic subdivision could however be applied and the percentage distribution within the groups was recorded. The subdivision was not carried further than that it could be applied by non-academically trained assistants specially trained for the present purpose by Brotzen.

The fact that the investigation for reasons quoted did not at first aim at a far-going separation of different species and ecotypes does not mean that the present author wants to deny the great value of such studies for pelagic Pleistocene stratigraphical purposes. The possibilities offered by taxonomical methods have been demonstrated by the work of among others W. Schott, F. B. Phleger and C. D. Ovey.

The following grouping was applied to the fraction $> 500\ \mu$:

Globigerina spp.
G. eggeri
G. inflata
G. sacculifera
G. conglobata
G. aequilateralis
G. rubra
Globorotalia
Pulleniatina obliquiloculata
Orbulina universa
Sphaeroidinella dehiscens
Sphaeroidina bulloides
Pyrgo
Uvigerina
Eponides
Other benthos

The differentiation of the foraminifera 150—500 μ was the following:

Globigerina
Globorotalia
Pulleniatina obliquiloculata
Orbulina universa
Sphaeroidinella dehiscens and Sphaeroidina bulloides
Uvigerina
Eponides
Other benthos

The benthonic foraminifera of all East Pacific samples investigated have been picked out, separated into genus or family groups, and mounted on cardboard slides. It is hoped that this material will be subjected to a special investigation by Brotzen or his coworkers.

In the two finest fractions, fragments of foraminifera are frequent. These fragments appeared to be of diagnostic value from a petrographical point of view and were also counted.

Besides the species and genera listed above, small numbers of other forms occur. No

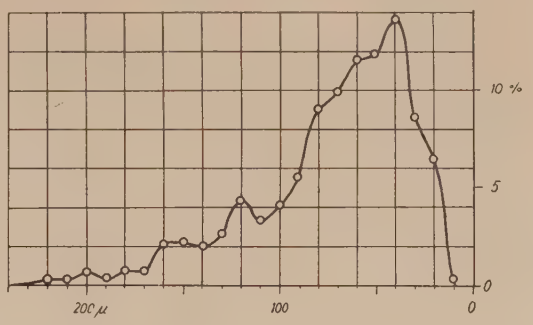

Fig. 4.9.4. Size distribution of radiolaria (*Cyrtoidea*) according to microscopical measurements of the length of 5 700 specimens. — Analyst, C. Jungk.

columns have been reserved in the diagrams for these infrequent occurrences, which are however quoted in the text when they were found to be statistically significant.

The foraminifera of the fraction $< 150\ \mu$ consist of benthos and to some extent of immature pelagic individuals. They have been kept for future investigation and are not treated in this volume.

In dealing with the present material, steps have been taken to make possible a judgement of the significance of the reported percentage values in each case. The punched card files thus contain the number of foraminifera per gram sample as well as the species or genus percentage values. When the number of foraminifera available in the sample were below 500, all individuals were counted — in other cases 500—1 000 were counted. Interpretation of statistical relationships has been preferred to interpretation of single values.

Radiolaria. Two different methods of approach were chosen for the study of radiolaria, one taking into account the absolute numbers of unspecified radiolaria $> 150\ \mu$, the other involving a study of distribution taxonomical groups within all size fractions. This latter study could be carried out only to a limited extent with regard to the resources available, whereas the recording of absolute numbers could be included in the routine investigation of the fraction 150—500 μ. As is seen from fig. 4.9.4 only seven

percent of the radiolaria (*Cyrtoidea*) are larger than 150 μ, and thus only the tail of the distribution falls within the currently investigated fractions. A quantitative treatment of the particles $< 150\ \mu$ necessitates special arrangements and is time-consuming. The finest fraction could therefore be subjected to quantitative fossil analysis in only a limited number of cases.

The distribution of *Cyrtoidea* shown in fig. 4.9.4 is based upon size measurements of 100 individuals in each of 57 different samples. The standard deviation of the 7.4 % which are larger than 150 μ is 3.2 %, and thus in nine trials of five hundred the radiolaria can be expected to disappear totally from the fraction $> 150\ \mu$ or to be represented in this fraction by as much as 15 % of the total radiolarian number. These variations of the area of the tail of the distribution curve are due to secondary selective dissolution which starts with the smaller individuals and possibly also to size distribution changes within the living assemblages. For the same reasons which render investigations of foraminifera $> 200\ \mu$ considerably less significant than investigations based on a smaller minimum size limit, the number of radiolaria found in the fraction $> 150\ \mu$ thus gives only a rough representation of the entire fauna. Such a rough measure can, however, be used with advantage in connection with the present work, the more so as the number of radiolaria in the Pacific deep sea deposits varies in geometrical progression and only statistical relationships are used as a basis for conclusions.

It should also be mentioned that the number of radiolaria left on the 150 μ sieve tends to be several percent higher than the number found under the microscope to have a minimum length of 150 μ (basis for fig. 9.5). This is due to the complicated shape of the fossils, which often makes it impossible to define accurately the size of a specimen (e. g. an *Euchitonia*) on the basis of sieving results (cf. Krumbein and Pettijohn, 1942, p. 124).

A study of the statistical distribution of *Cyrtoidea* in the present material has been published by Weibull (1949).

Diatoms. The study of the diatoms has been restricted to the very marked changes in size distribution of *Coscinodiscus nodulifer*. The investigation was carried out on unfractioned material and the methods of preparation and measurement have been described below (§ 4.9.2).

The microscopical measurements were in the beginning carried out by Dr. R. W. Kolbe and later on by a team under his supervision, consisting of Mrs. G. Erdtman, Mr. C. Asker, Mr. A. Jerbo and Mr. A. Silfversparre. Approximately 350 individuals were measured in each sample.

Other findings. Besides the groups treated above there are incidental occurrences of other fossils and of mineral grains $> 150\ \mu$, which have also been reported. Only in the clay samples these findings are frequent enough to require a tabular presentation. The punched-card file comprises the most frequent groups for the cores 48 to 57. In some cases (e. g. »Mollusc fragments») fairly big amounts were found of undeterminable fossil fragments, which were, however, counted and reported.

The following groups are included in the card file (clay area part):

Sponges. The number corresponds to the number of spicules found per gram of salt free sediment.

Teeth. Includes fish teeth and annelide jaws. Only specimens $< 500\ \mu$ have been found.

»*Mollusc fragments*» are fragments of calcareous shells which may belong to pteropodes. Entire shells of corresponding type have not been found in the material. The fragments are compact, semitranslucent and opalescent. Their curvature indicates the size of the entire fossil to be a few millimeters.

Manganese nodules.

Palagonite and unaltered volcanic glass.

Other mineral grains. These were not identified in connection with the microscopical routine analysis and were usually rare. In such cases where the frequency was high enough to be of stratigraphical interest the grains were mounted and investigated under the polarization microscope.

Other findings, which are not listed in the card file, are spines of echinoids, faecal pellets, beaks of cephalopodes, ostracodes, fish scales, bone fragments, otoliths, e. a. In many cases special mountings were made. The findings are further mentioned in connection with the stratigraphical descriptions.

In organizing the microfossil investigation the author had the great advantage of being advised by Dr. F. Brotzen, Stockholm, whose great kindness and unlimited helpfulness have been indispensable factors in undertaking the work. Also during the course of the investigation Dr. Brotzen's help and advice have been extremely valuable.

Most countings and determinations were carried out by Miss Isolde Müller, Stockholm.

4.9.2 Treatment of the samples.

1 ± 0.01 g of the dry sediment was boiled with 30 % hydrogen peroxide (Gripenberg, 1934, p. 59—60) and the suspension washed on a double woven bronze wire sieve with an effective mesh width of 150 μ. The material passing the sieve was collected in a 1 000 ml beaker and allowed to settle one hour, after which the particles still suspended were decanted. The residue was transferred to an evaporation dish, once again decanted, and finally dried. This fraction contains most particles between 150 and 7 μ, as well as a small amount of particles smaller than 7 μ.

The material on the 150 μ sieve was dried and sieved in a dry state for appr. five minutes. Particles passing the sieve were combined with the finest fraction. The coarser fraction, finally, was divided into two parts by passing it through a 500 μ-sieve. The sieved material was stored in glass vials.

The material coarser than 500 μ consisted almost entirely of foraminifera. As the number of individuals rarely exceeded 500, the whole fraction was examined. The most commonly used enlargements were 40 and 100 $\times$. The numbers counted were recorded by means of electrical counting relays. Several details of the methods of investigation were directly taken over from Brotzen (1950).

The fraction 150—500 μ contained up to 20 000 foraminifera and sometimes more than 100 000 radiolaria; therefore it had to be quartered before examination. As the numbers found have to be referred to a one gram basis, the relation between the total sample and the split part which was examined must be known. This was attained by weighing both the total fraction and the split part on a torsion balance; the number of individuals counted multiplied by the quotient total/split gives the number of individuals in one gram of the sediment. The apparatus used for quartering was the Microsplitter devised by Otto (1933). Any error in counting will be multiplied by the split quotient, which varied between 1 and approx. 30. The resultant error was estimated at 4 % or less of the values reported as far as comparatively isometrical grains are concerned.

Samples of the finest fraction (< 150 μ) were mounted in canada balsam, hyrax or other mediums, the choice depending upon the nature of the investigation. Material prepared for the study of siliceous structures and stable minerals was first freed from carbonates by treatment with hydrochloric acid then washed and collected by centrifugation or sedimentation. In those cases where the results of the examination of the finest fraction were to be referred to a one gram basis, the material was suspended in distilled water, diluted to a suitable, measured volume and an aliquot part of it extracted by means of an adjustable microsyringe during stirring. The content of the syringe, usually

a few hundred cubic millimeters, was transferred to a cover glass on a heating plate and the water driven off. The syringe was washed twice and the wash waters transferred and evaporated as the sample. The accuracy of the syringe was $\pm$ 0.01 ml and the total volume of the suspension usually was 100 ml $\pm$ 0.1.

Size measurements were carried out by means of ocular micrometers, calibrated to a standard.

4.10 Numerical presentation of the results

The numerical results of the East Pacific investigation comprise more than 50 000 values. For the purpose of comparing these with each other and of interpreting them the tabular representation did not appear to be sufficiently flexible. In the present report, therefore, the tables of primary results have largely been substituted by graphical representations which allow a more surveyable synoptical treatment of the material. As it was supposed that the tables will be used in comparatively few cases only, it was regarded suitable to reproduce the primary values in punched card files which will make extended studies of the material possible for other workers. Duplicates of the card files can be obtained from the Institute of Oceanography, Box 1038, Göteborg 4, or from the author.

References

Arrhenius, G. (1947). Den glaciala lerans varvighet. — Sver. Geol. Unders. Ser. C nr 486.

Arrhenius, O. (1929). Die Phosphatfrage II. Die Phosphatanalyse. — Zeitschr. f. Pflanzenernährung, Düngung u. Bodenkunde, Teil A, Bd 14, 185.

Bell, F. and Doisy, E. A. (1920). Rapid colorimetric methods for the determination of phosphorus in urine and blood. — J. Biol. Chem. 44.

Brandt, K. (1902). Beiträge zur Kenntniss der Colliden. — Arch. f. Protistenkunde, Bd 1.

Brotzen, F. (1936). Foraminiferen aus dem schwedischen untersten Senon von Eriksdal in Schonen. Sver. Geol. Unders. Ser. C 396.

——— (1950). Methods and techniques in routine work. — The Micropaleontologist vol. 4.2 p. 18.

Christensen, B. E. Williams, R. J. and King, A. E. (1937). Organic oxidation equivalent analysis: III. J. A. C. S. *59*, 293.

Christensen, B. E, Simkins, G. and Hiatt, V. (1940). A simple apparatus and procedure for the determination of the carbon content of the soil. — Soil Sci. *49*, 51.

Clark, N. A. and Ogg, C. L. (1942). A wet combustion method for determining total carbon in soil. Soil Sci *53*, 27.

Clark, W. M. (1928). The determination of hydrogen ion concentration. — Baltimore.

Forslind, E. (1948). The clay-water system I. — Swed. Cement and Concrete Research Institute, Bull. no 11.

Gripenberg, S. (1934). Sediments of the North Baltic and adjoining seas. — Fennia 60, nr 3.

Haeckel, E. (1887 a). Die Radiolarien. Eine Monographie.

——— (1887 b). Report on the Radiolaria. — Challenger Report, Vol. 18.

Hey, M. H. (1930). Studies on zeolites I. General review. — Min. Mag. 22, p. 422.

Hillebrand, W. F. (1919). Analysis of silicate and carbonate rocks. — U. S. G. S. Bull. 700.

Krumbein, W. C. and Pettijohn, F. J. (1942). Manual of sedimentary petrography. — New York.

Kuenen, Ph. H. and Migliorini, C. I. (1950). Turbidity currents as a cause of graded bedding. — Jour. Geol. 58: 91.

McBain, J. W. (1932). The sorption of gases by solids. — London.

Nutting, P. G. (1944). Grain densities, weight humidity, and weight temperature relations of Carnegie Pacific bottom samples. — Carnegie Inst. Wash. Publ. 556.

Ostwald, W. (1933). Unesma Farbtafeln. — Grossbothen.

Otto, G. H. (1933). Comparative test of several methods of sampling heavy mineral concentrates. — Jour. Sed. Petr. 3.30.

Mitscherlich, F. A. (1923). Bodenkunde für Land- und Forstwirte. 4th ed. — Berlin.

Parnas, J. K. and Wagner, F. (1938). Ueber die Ausführung der Stickstoffbestimmung nach Kjeldahl in der Modifikation von Parnas und Wagner. — Ztschr. Analyt. Chem. 114.

Phleger, F. B. (1948). Foraminifera of a submarine core from the Caribbean sea. — Medd. Oc. Inst. Göteborg nr 16.

——— (1951). Ecology of foraminifera, Northwest Gulf of Mexico. Part 1. — Geol Soc Am Mem 46

Pregl, F. and Grant J. (1945). Quantitative organic microanalysis. Revised by I. Grant. 4th Ed. — London.

Puri, A. N. (1925). A critical study of the hygroscopic coefficient of soil. — J. Agr. Sci. 15, p. 272.

RAMAGE, W. D. and MILLER, R. C. (1945). The salt error of cresol red. — J. A. C. S. 47, 1230.

SCHOTT, W. (1935). Die Foraminiferen in dem aequatorialen Teil des Atlantischen Ozeans. — Wiss. Ergebn. Deutsch. Atlant. Exp. Meteor. 3.3 43.

Statens Järnvägars Geotekniska Kommission. Slutbetänkande 1922. — Statens Järnvägars Geotekn. Medd. 2.

SVERDRUP, H. U., JOHNSON, M. W. and FLEMING, R. H. (1946). The Oceans. — New York.

REVELLE, R. (1944). Marine bottom samples collected in the Pacific Ocean by the Carnegie on its seventh cruise. — Carnegie Inst. Wash. Publ. 556.

TISELIUS, A. (1936). Adsorption and diffusion in zeolite crystals. — J. Phys. Chem. *40*, 223.

WEIBULL, W. (1949). A statistical analysis of the size of *Cyrtoidea* in sediment cores from the East Pacific ocean. — Nature, *164*, 1047.

WENNER, C-G. (1949). Fakta om Sveriges lerförekomster. Geol. Fören. Förhandl. *71*, 435.

CONTENTS

Page

ARRHENIUS, GUSTAF: Sediment Cores from the East Pacific.

Part 1. Properties of the Sediment and their Distribution 1

Part 2. Description of the Sediment Cores 93

Appendix: Description of Plates. Plates 2.6.1.—2.62.

Part 3. Geology of the East Equatorial Pacific 187

Part 4. Methods Used at the Study of the Sediment Cores 203

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